Charge azimuthal correlations at RHIC and LHC

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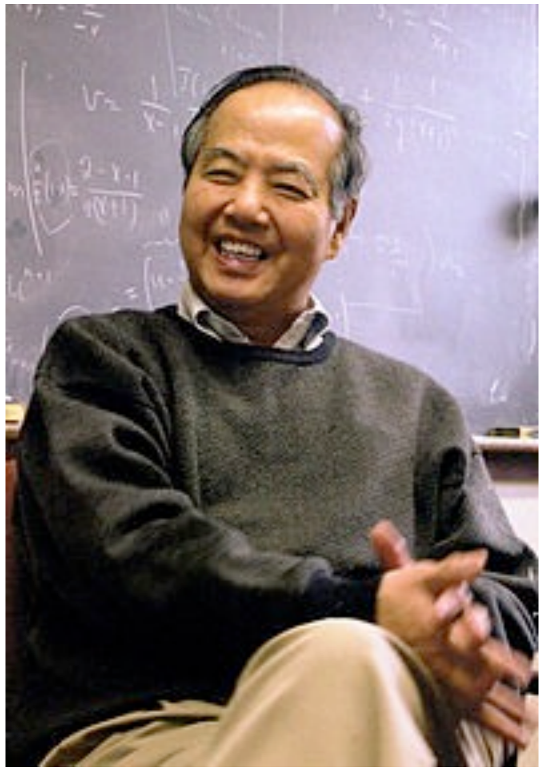
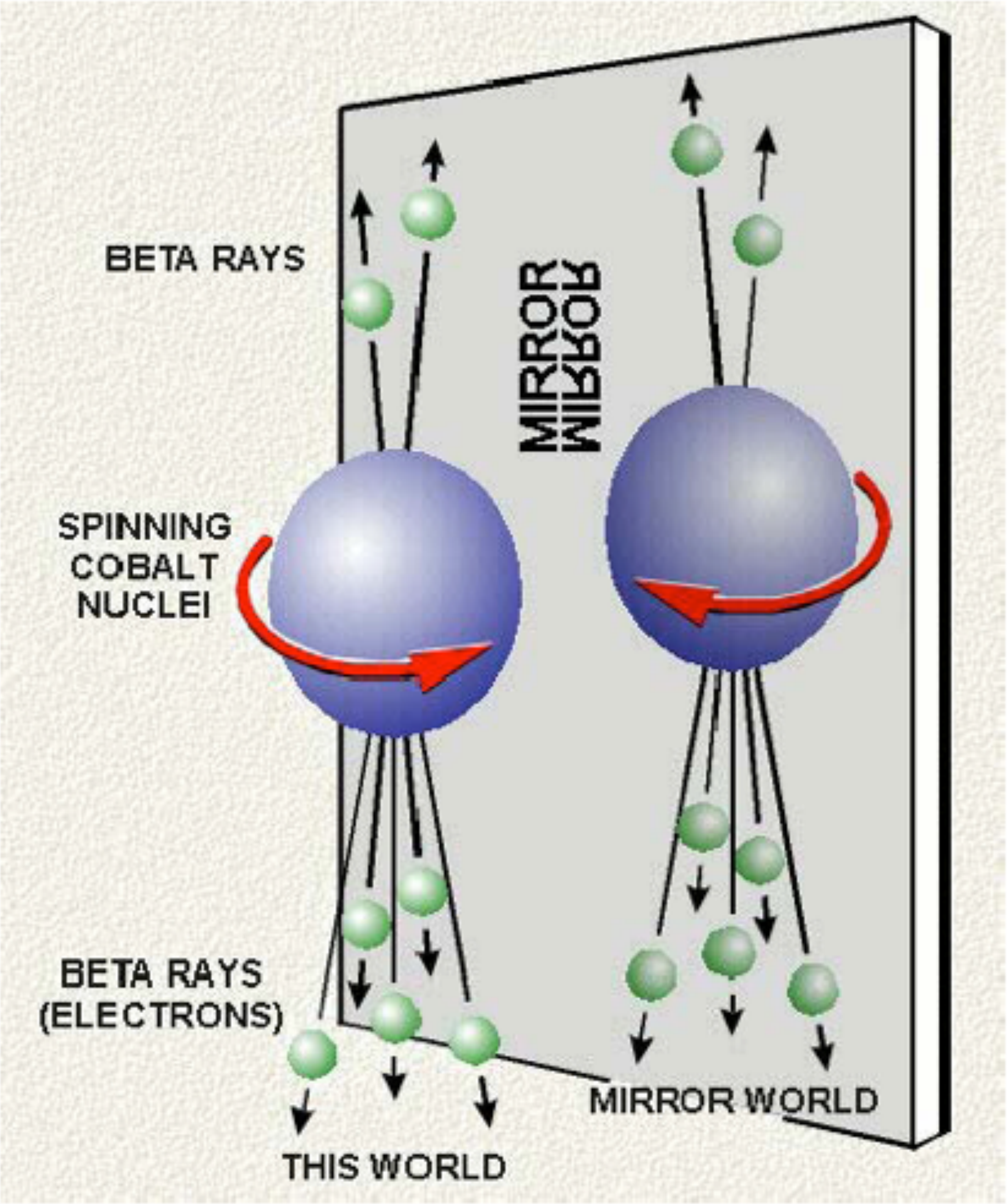
This work is in collaboration with Dr. Bin Zhang (ASU).

Outline

- Introduction
- Charge correlations at top RHIC energy
- Charge correlations at low RHIC energies
- Charge correlations at LHC energy
- Outlook & Summary

Parity Violation in Weak Interactions

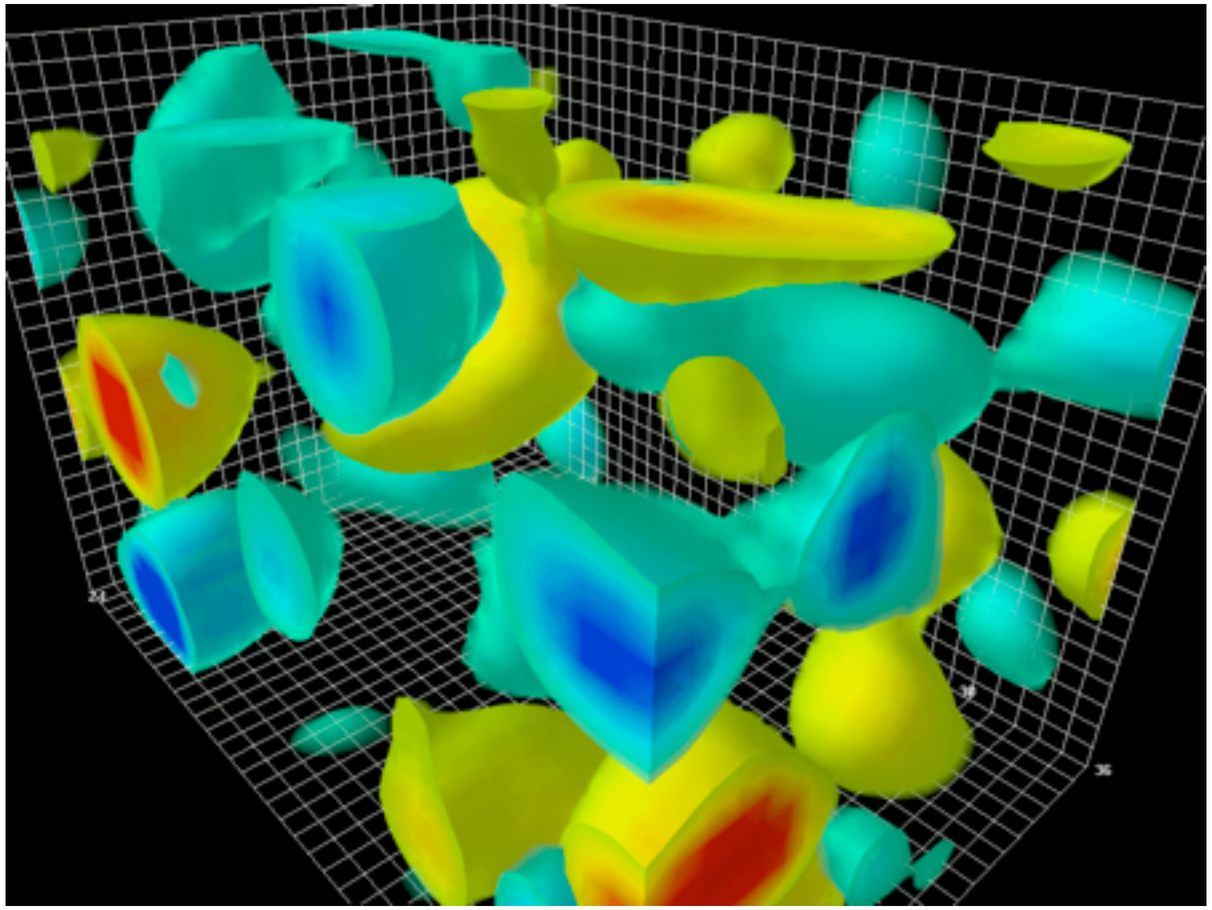


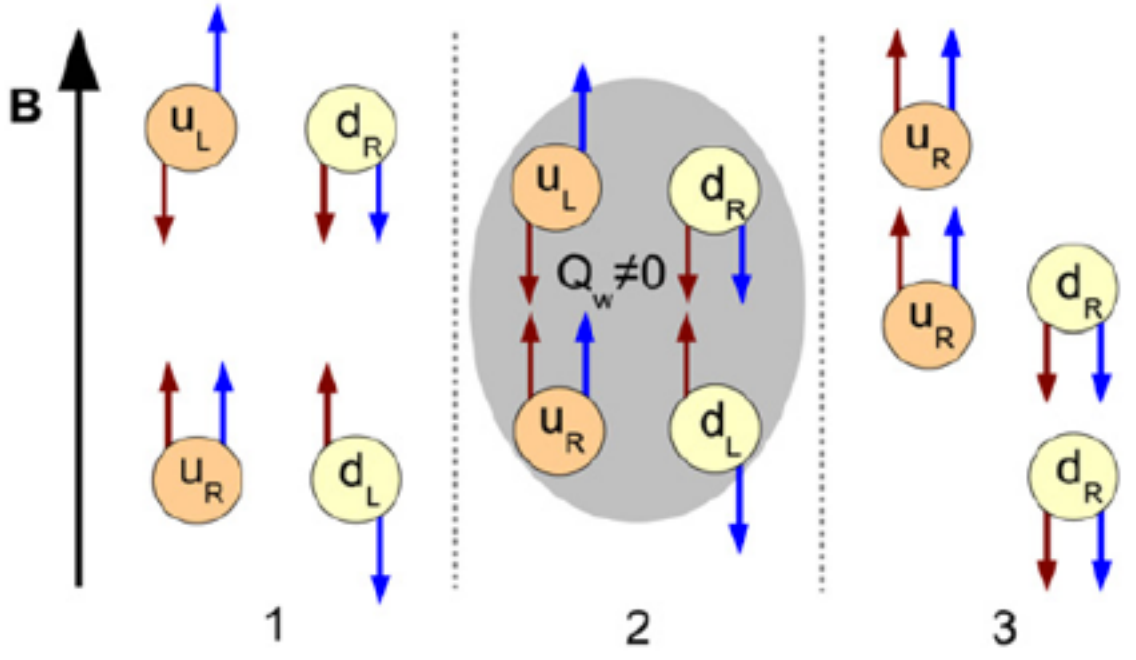


C.S. Wu, 1912-1997

- Lee and Yang won Nobel Prize in 1957, because of prediction about parity violation in weak interactions and confirmation by Wu’s Cobalt experiment.
- How about parity conservation in strong interactions?

PV in SI: Chiral Magnetic Effect

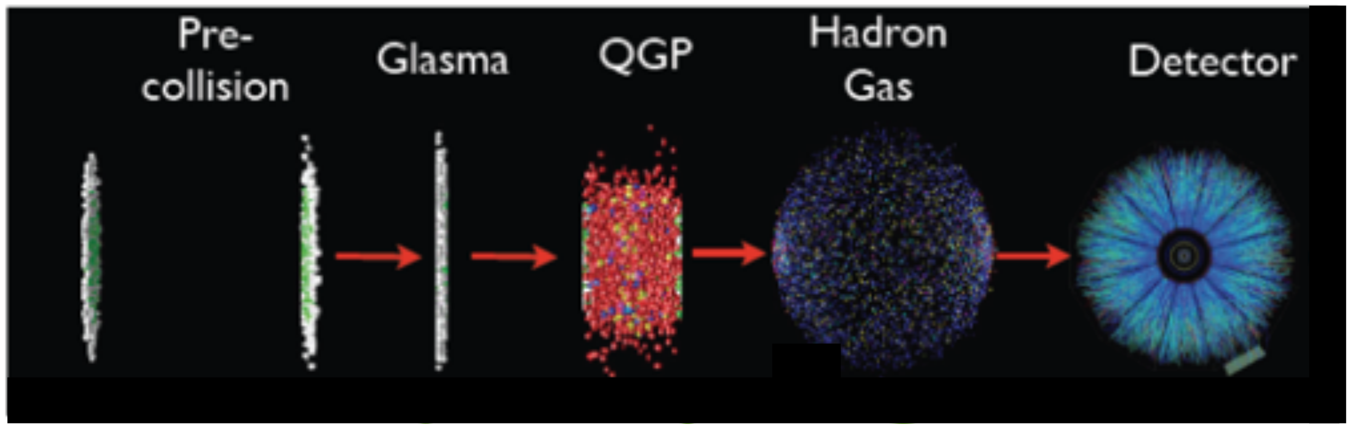


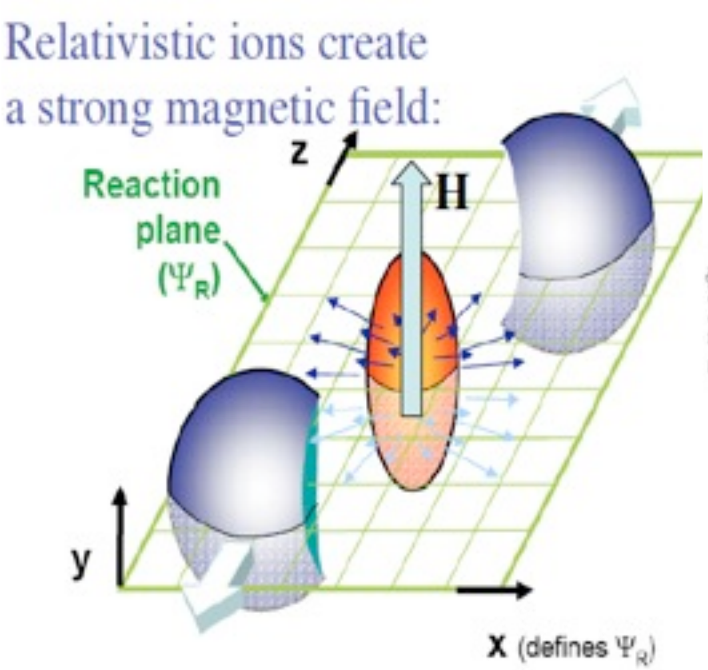


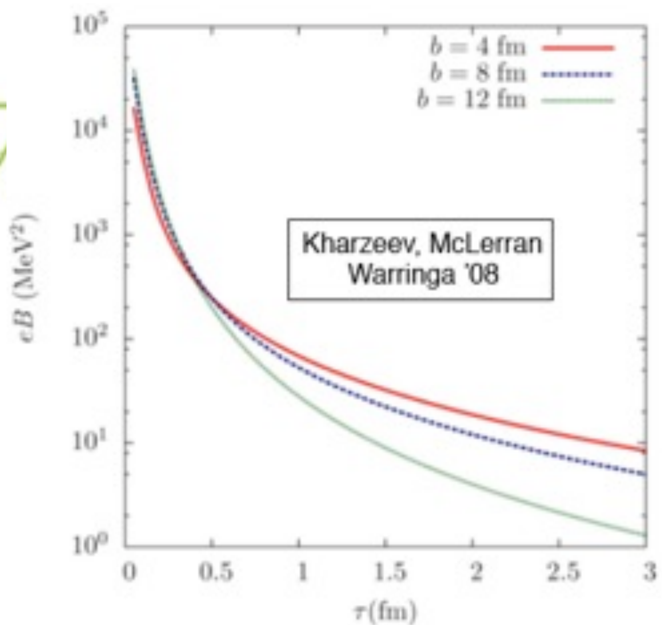
Red arrow - momentum; blue arrow - spin;
In the absence of topological charge no asymmetry between left and right (fig.1) ;the fluctuation of topological charge (fig.2) in the presence of magnetic field induces electric current (fig.3)

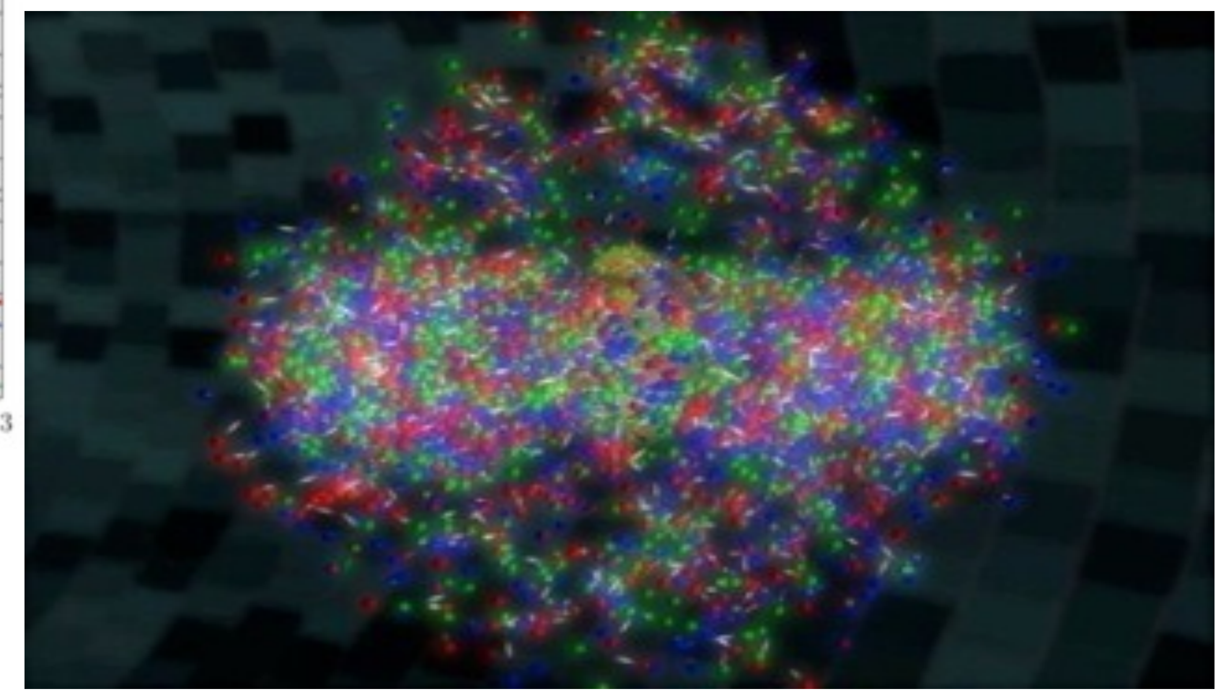
- Initial fluctuations of topological charge in QCD vacuum → P and CP odd metastable domains → Charge separation in the direction of magnetic field → CME indicates that parity can be locally violated in strong interactions.

Where is CME?





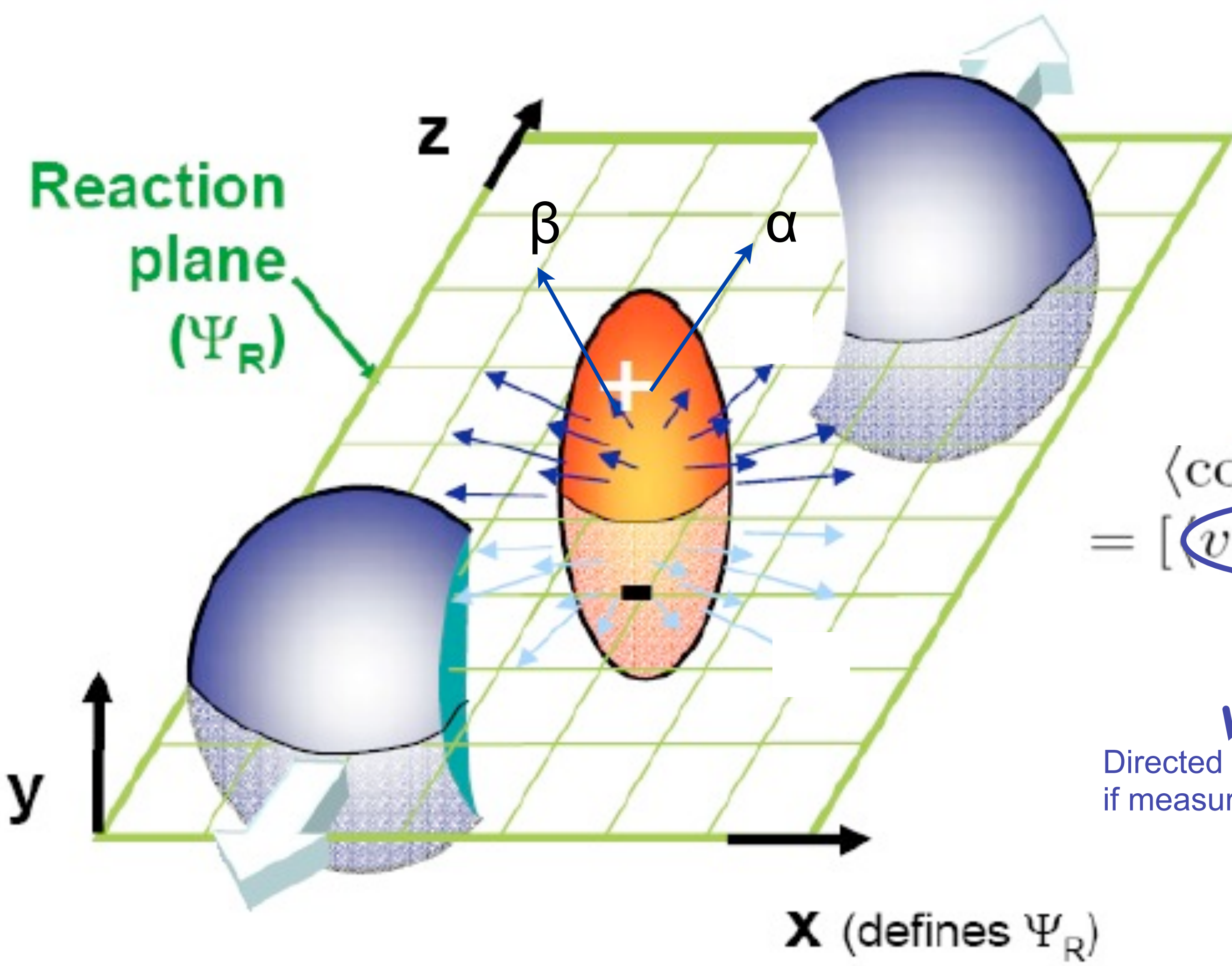




CME requirements:
(1) strong magnetic field ✓
(2) fluctuating QCD source ✓

How to observe CME experimentally? Two obeservbles so far,

Exp. observable I: charge azimuthal correlation



$$\frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2v_{2,\alpha}\cos(2\Delta\phi) + \ldots$$
$$+ 2a_{1,\alpha}\sin(\Delta\phi) + 2a_{2,\alpha}\sin(2\Delta\phi) + \ldots,$$

$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{in}] - [\langle a_\alpha a_\beta\rangle + B_{out}]$$

Directed flow: vanishes
if measured in a symmetric rapidity range

Non-flow/non-parity effects:
largely cancel out

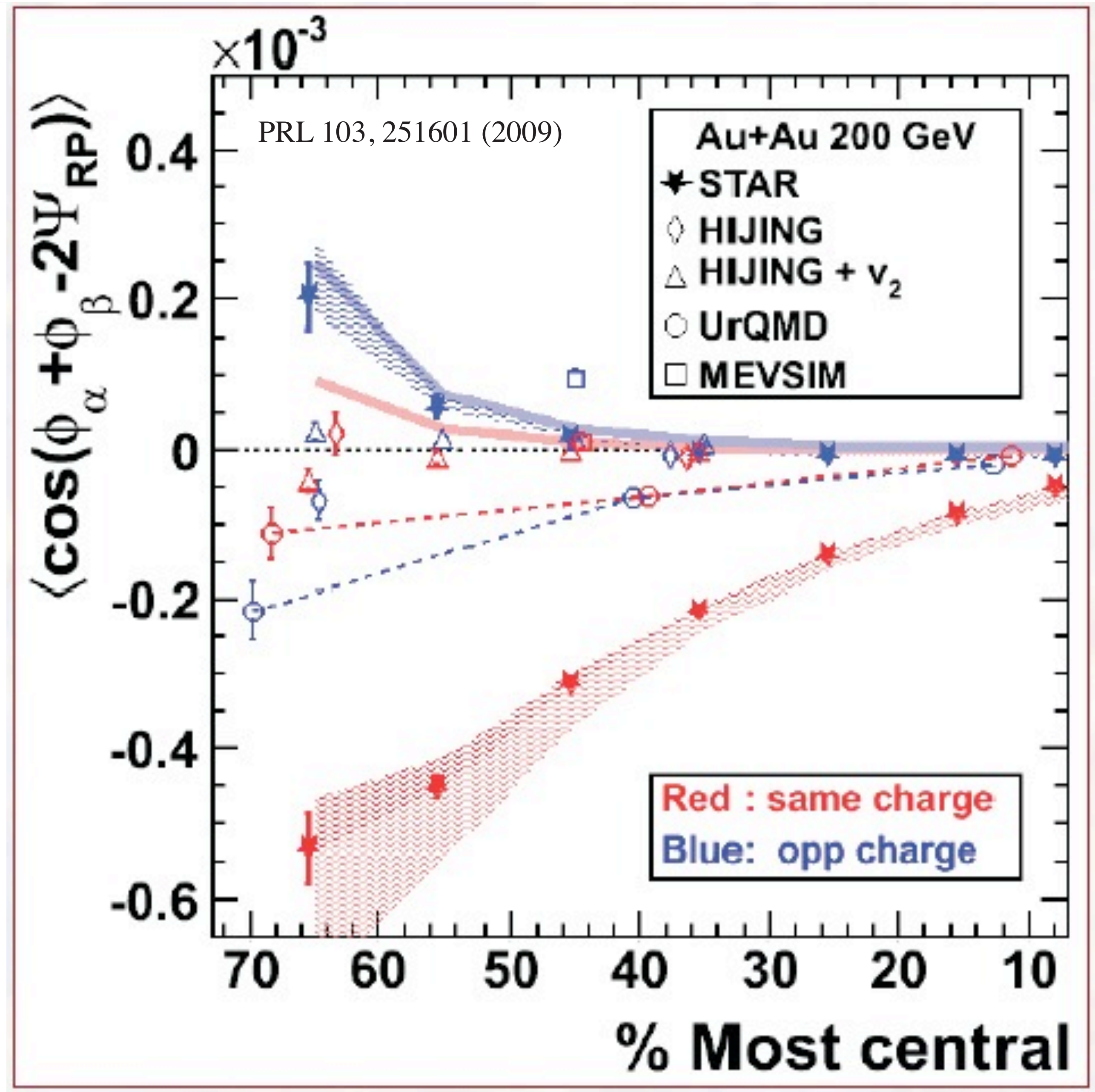
P-even quantity:
still sensitive to charge
separation

$$a^k a^m = \langle \sum_{ij} \sin(\varphi_i^k - \Psi_R)\ \sin(\varphi_j^m - \Psi_R)\rangle$$

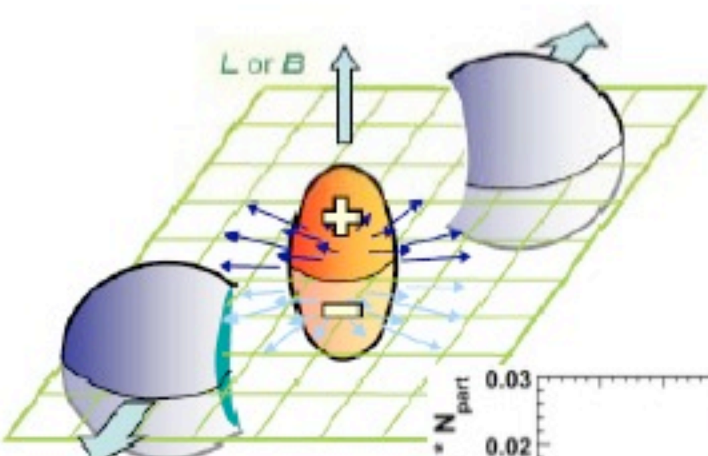
CME expects: $a^+a^+ = a^-a^- > 0; \quad a^+a^- < 0$

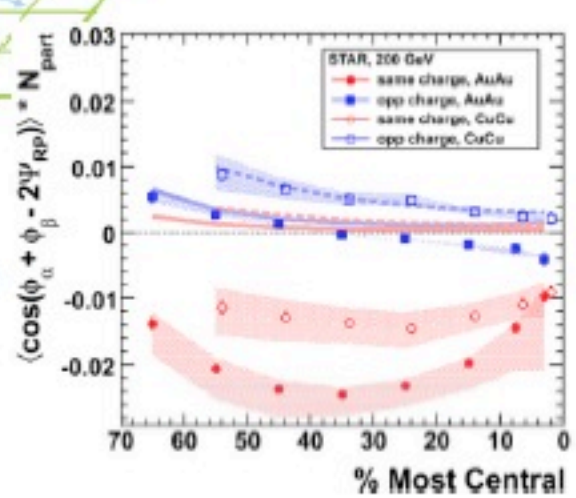
Exp. results about charge azimuthal correlation

- Same-charge is negative and opposite-charge is positive, which is consistent with CME expectations.
- Bigger amplitude in same-charge correlations compared to opposite-charge.
- Large difference in same-charge vs opposite-charge correlations in the data compared to models.



Exp. observable II: charge asymmetry correlation





STAR, PRL 103, 251601 (09); PRC 81, 054908 (10).

$$A_{\pm,UD} = \frac{N_{\pm,up} - N_{\pm,down}}{N_{\pm,up} + N_{\pm,down}}$$

$$A_{\pm,LR} = \frac{N_{\pm,left} - N_{\pm,right}}{N_{\pm,left} + N_{\pm,right}}$$

Chiral magnetic effect:

- LPV + large magnetic field

→**charge separation** along the system angular momentum.

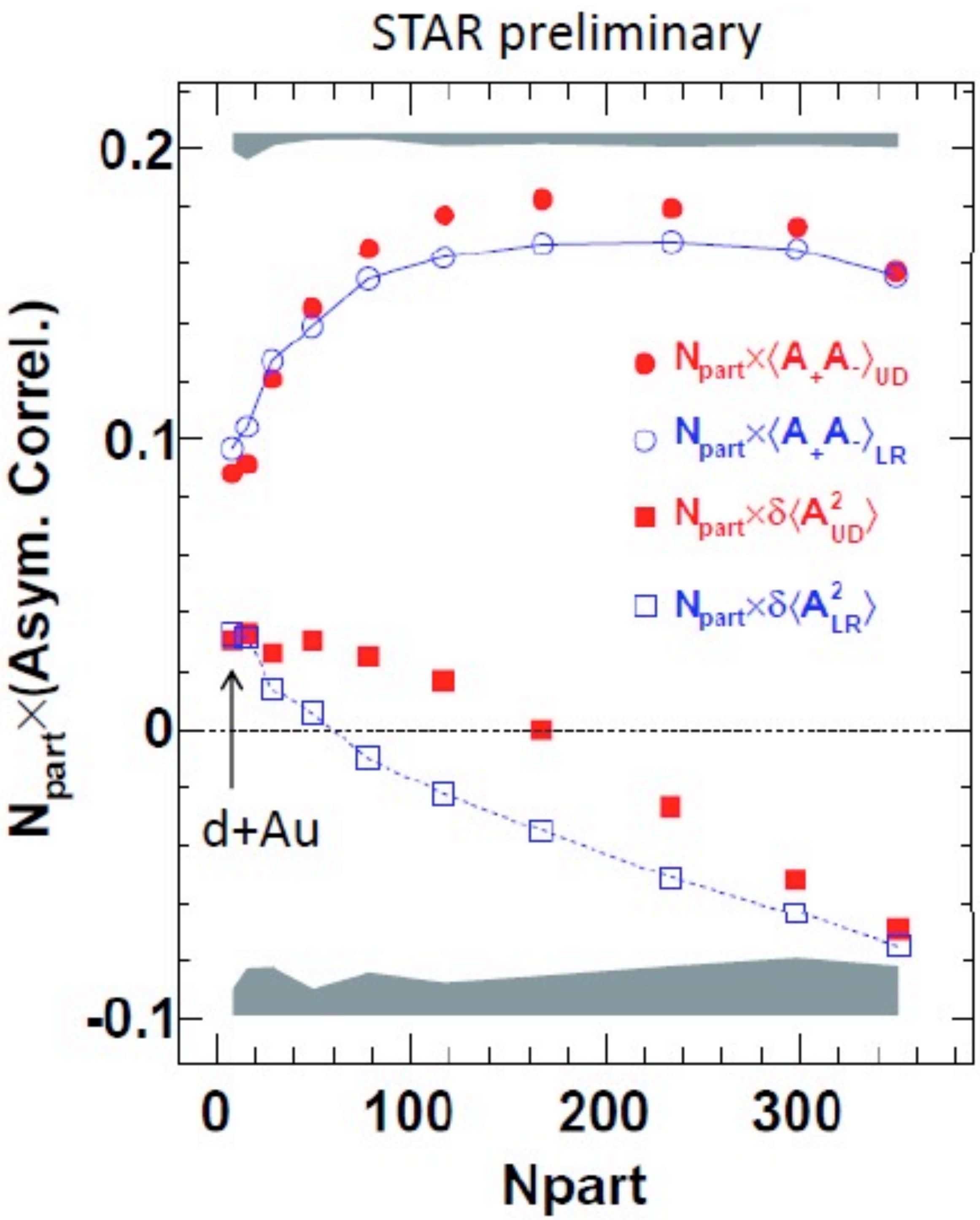
Kharzeev et al. NPA 803 (2008) 227.

CME effects in UD. LR is null-reference.

CME expectations:

- A_{+UD} and A_{-UD} are anti-correlated
  → $\langle A_+A_-\rangle_{UD} < \langle A_+A_-\rangle_{LR}$
- Additional dynamical fluctuation broadens $A_{\pm UD}$ distributions
  → $\langle A_\pm^2\rangle_{UD} > \langle A_\pm^2\rangle_{LR}$

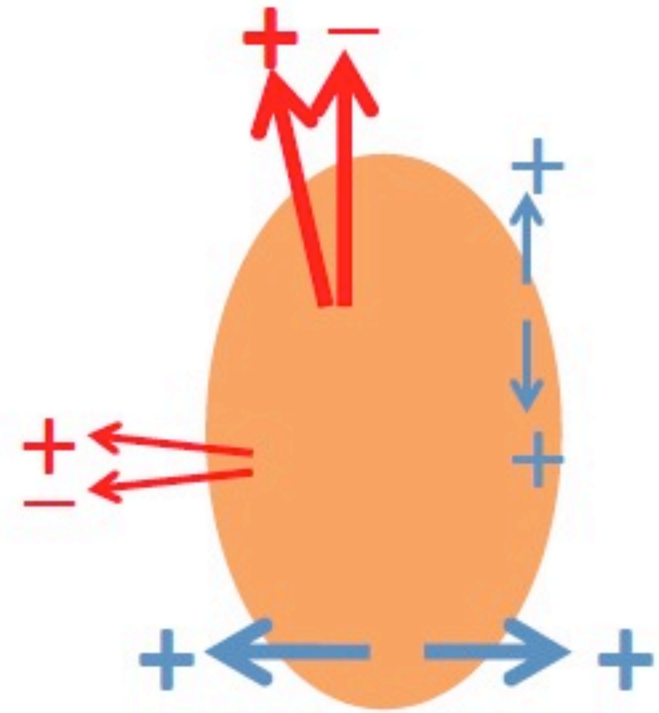
Exp. results about charge asymmetry correlation



- Oppo-sign aligned; $\langle A_+A_-\rangle_{UD} > \langle A_+A_-\rangle_{LR}$

  CME expects: $\langle A_+A_-\rangle_{UD} < \langle A_+A_-\rangle_{LR}$

  Contradicts CME expectations.

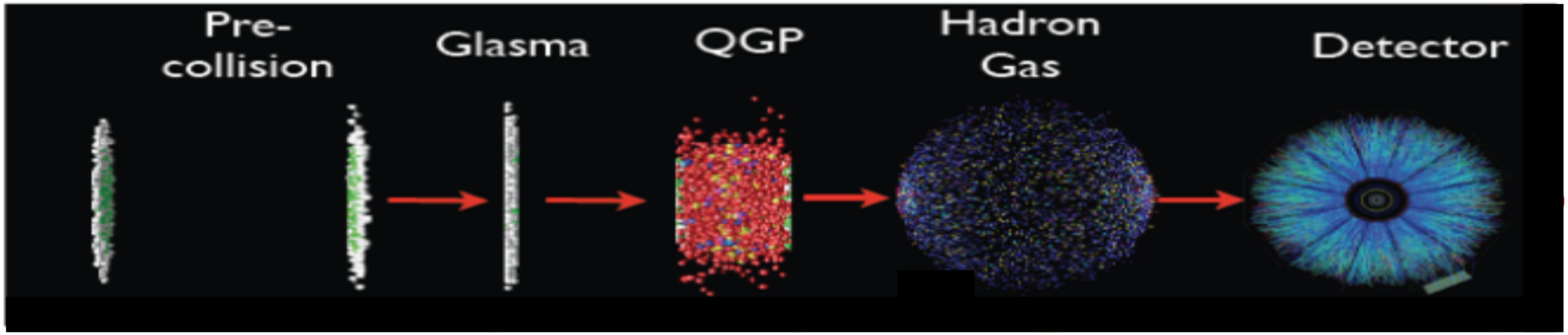


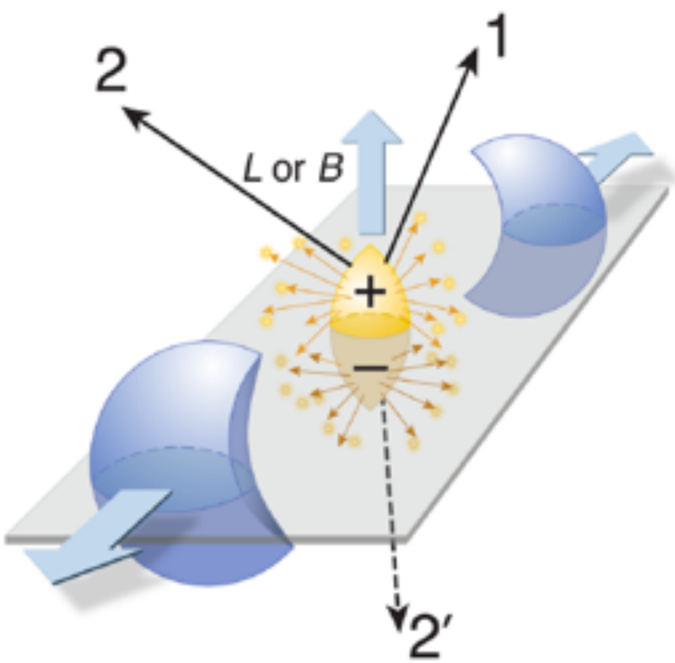
- Same-sign back-to-back in central, unexpected from *only* CME

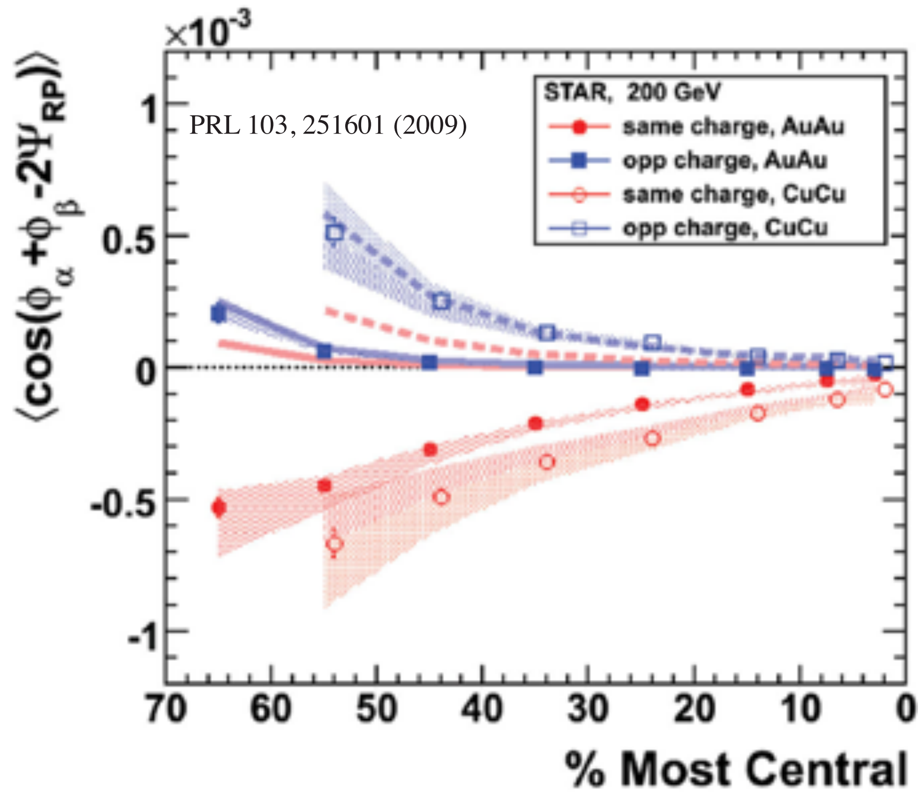
  Data: $\langle A^2\rangle_{UD} > \langle A^2\rangle_{LR}$

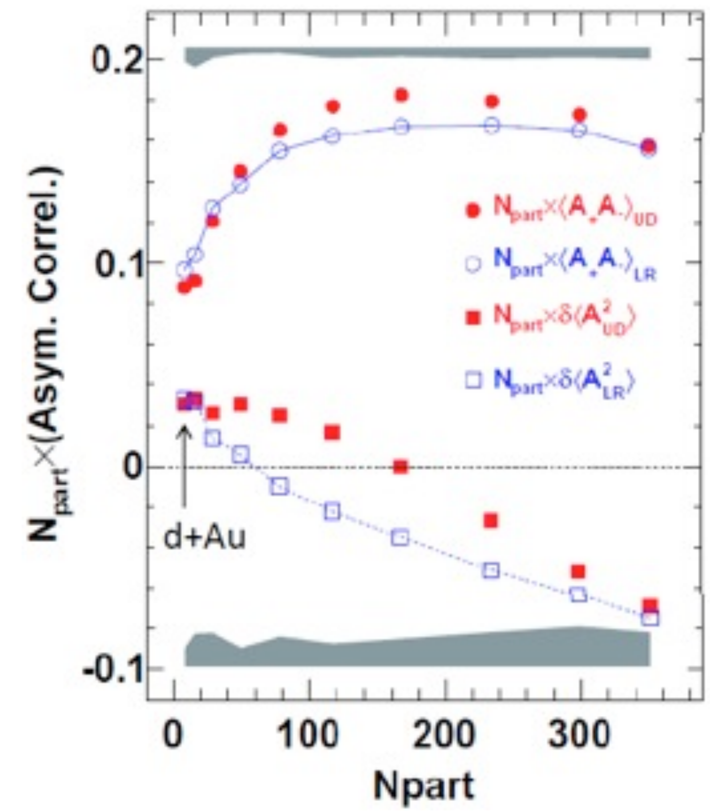
  CME expects: $\langle A^2\rangle_{UD} > \langle A^2\rangle_{LR}$

Can a CME signal be observed?









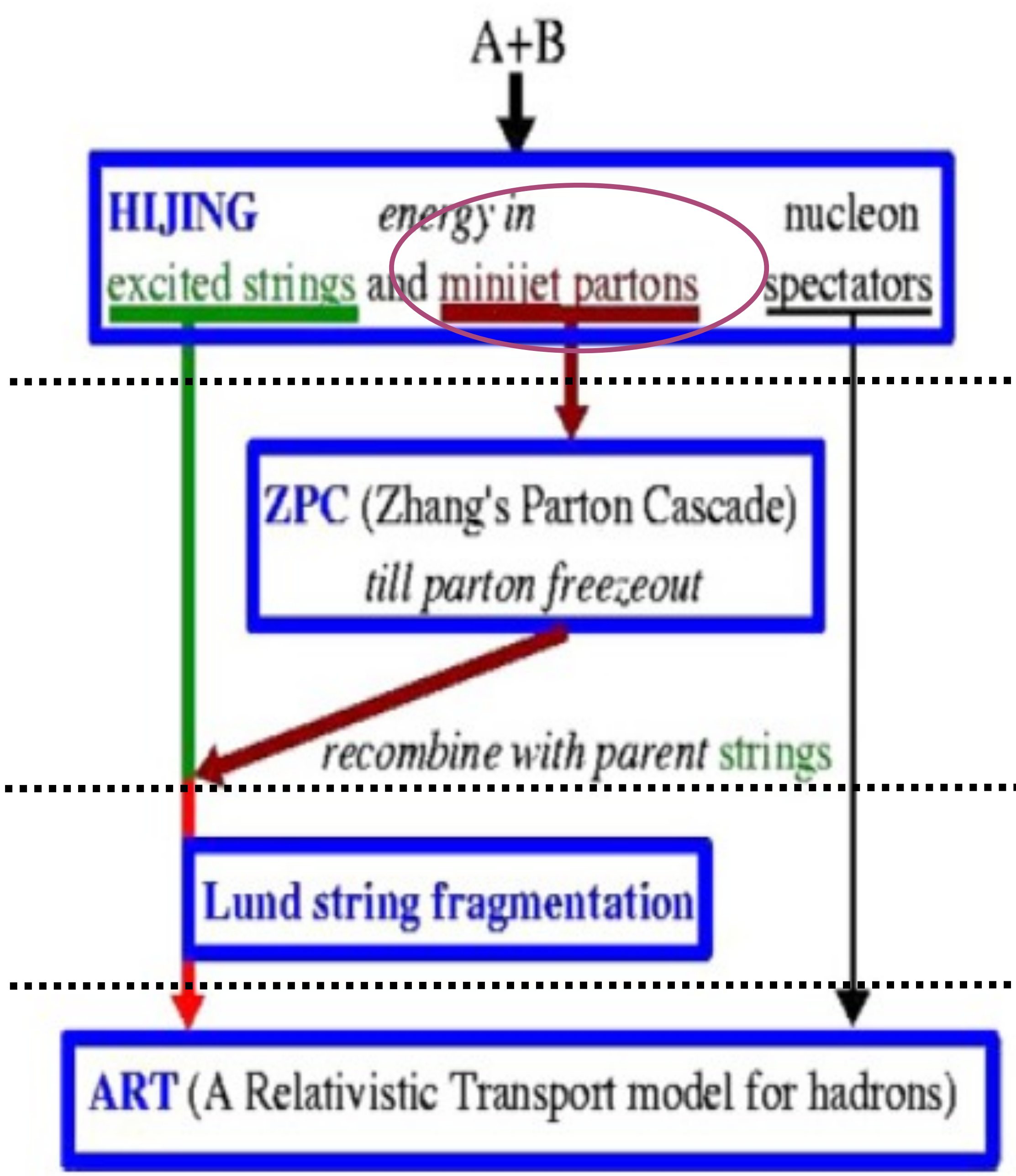
•Relativistic heavy-ion collision is a multi-stage dynamical evolution, then...

Can initial charge separation survive from final strong interactions?

AMPT model introduction

a multi-phase transport model

(1) Default AMPT Model



(2) Melting AMPT Model

(C. M. Ko and Z. W. Lin et al. PRC 72, 064901 (2005))

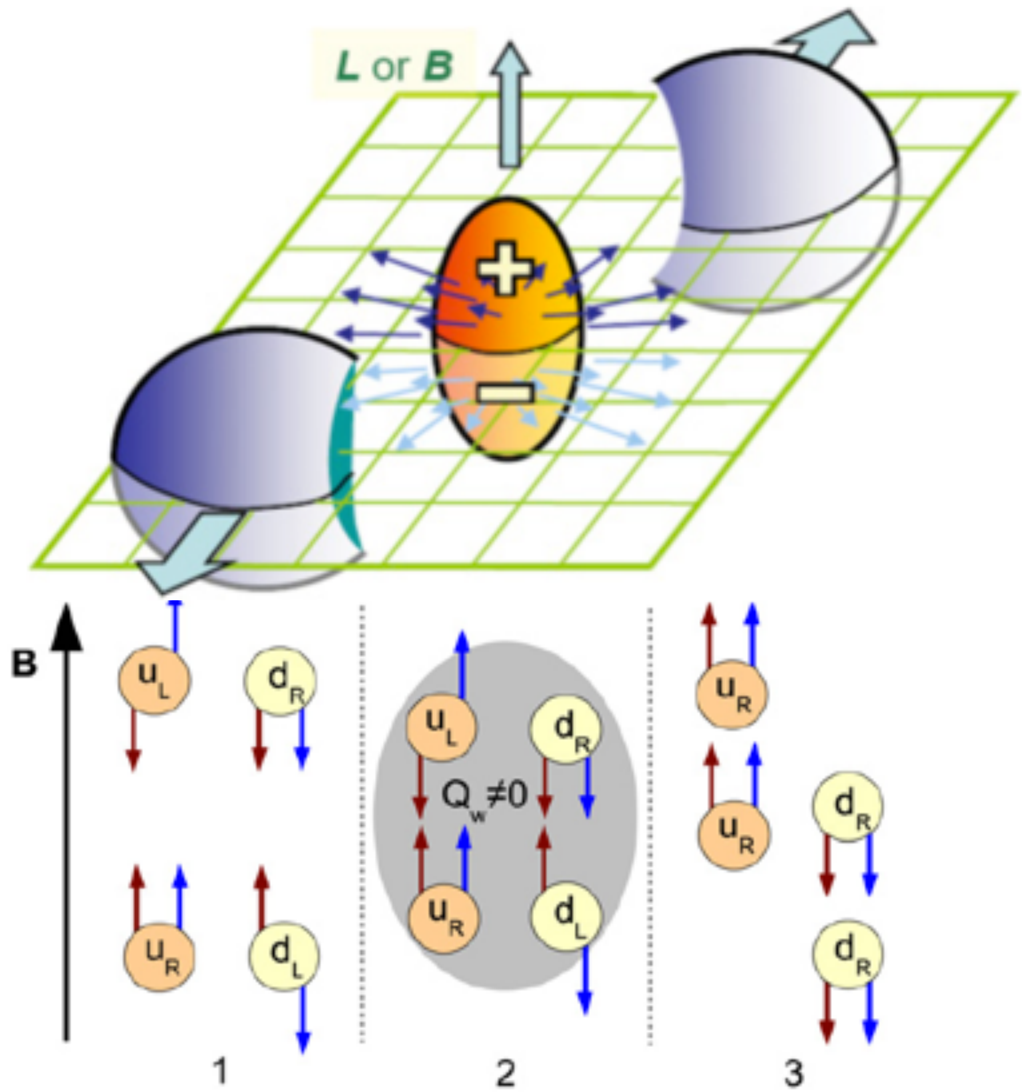
(1) initial condition

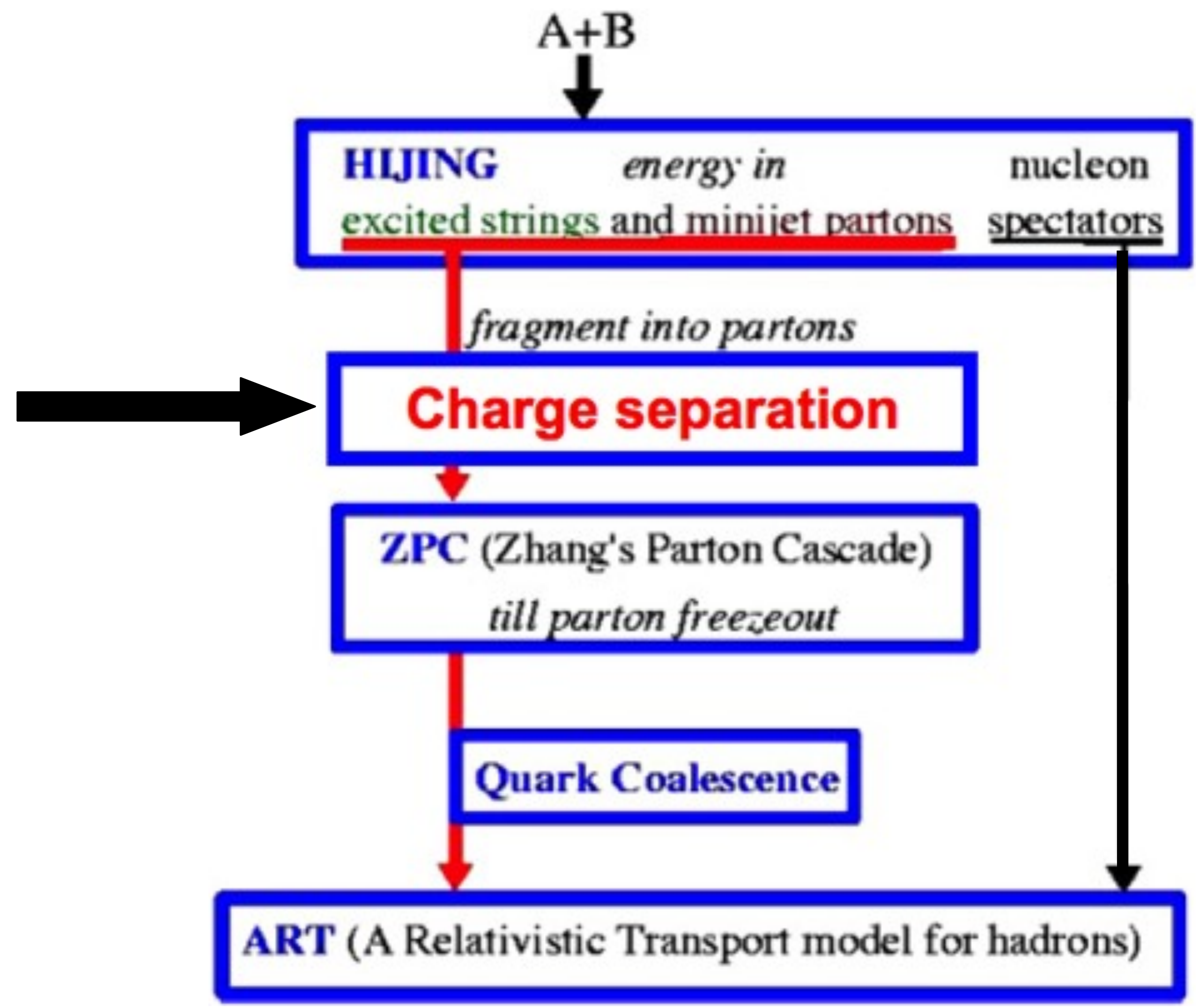
(2) parton cascade

(3) hadroni-zation

(4) hadronic rescattering

How to study charge separation by AMPT model





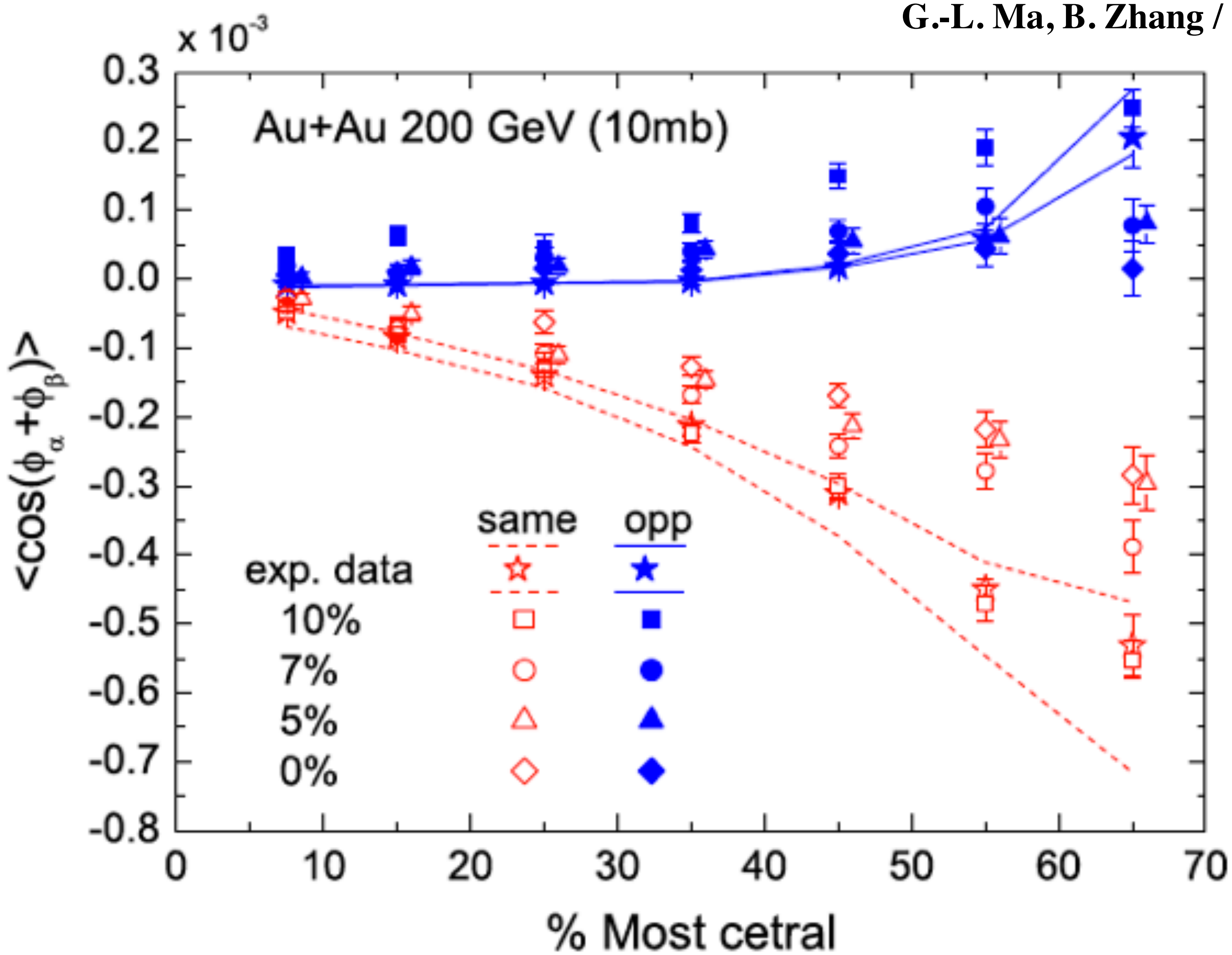
- **We include initial charge separation mechanism into AMPT model.**

We switch the p_y values of a fraction of the downward moving u quarks with those of the upward moving u-bar quarks, and likewise for d-bar and d quarks.

- **We will focus on final interaction effects on the charge separation, including parton cascade, hadronization, resonance decays.**
- **Resonance decays are implemented to ensure charge conservation.**

AMPT results about <cos(φ_α+φ_β)>

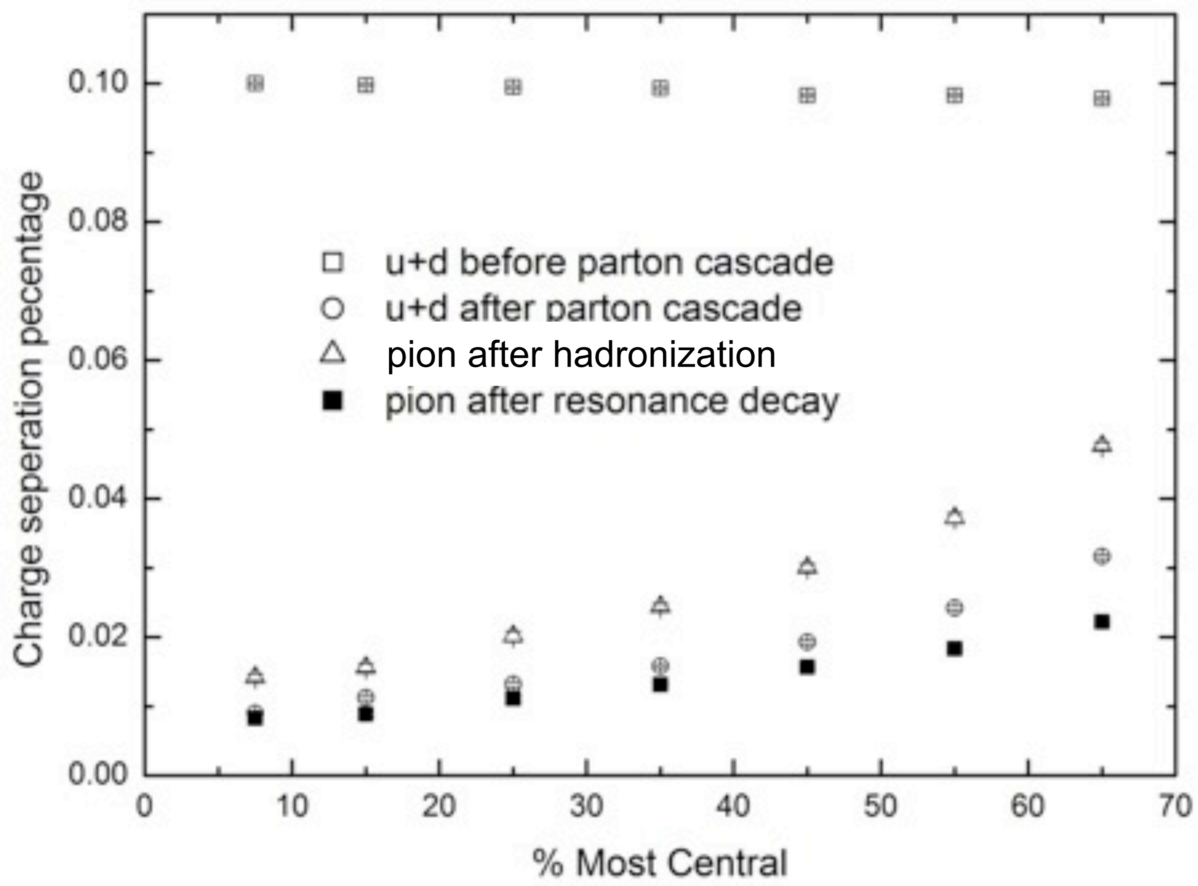
G.-L. Ma, B. Zhang / Physics Letters B 700 (2011) 39–43

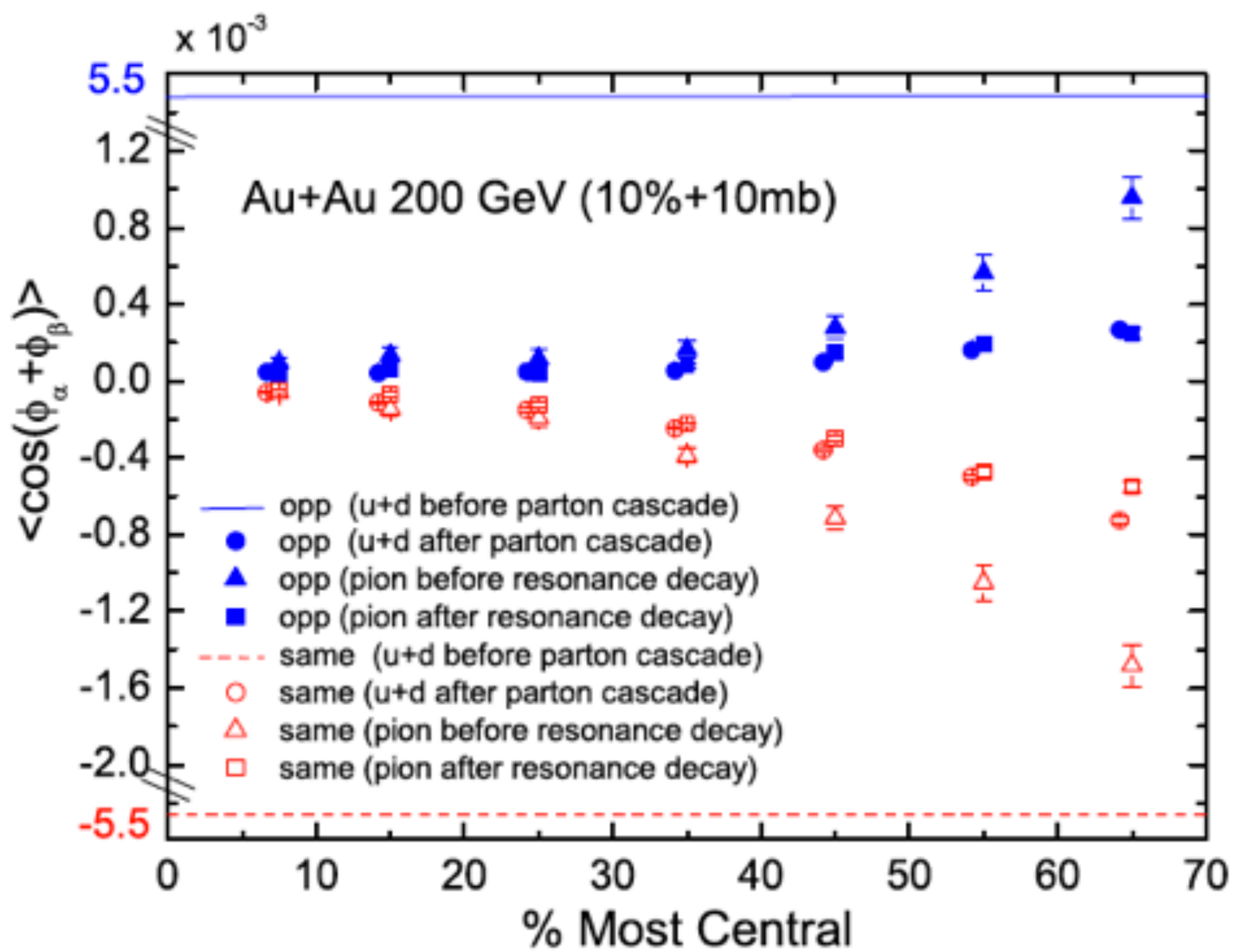


- For same-charge, 10% initial charge separation can describe data.
- For opposite-charge, initial charge separation is not necessary for all centralities except 60-70%.
- For centrality of 60%-70%, 10% initial charge separation can describe both same-charge and opposite charge.

It is challenging to observe an initial charge separation of <5% in the presence of strong final state interactions.

Final state effects on <cos(φ$_\alpha$+φ$_\beta$)>

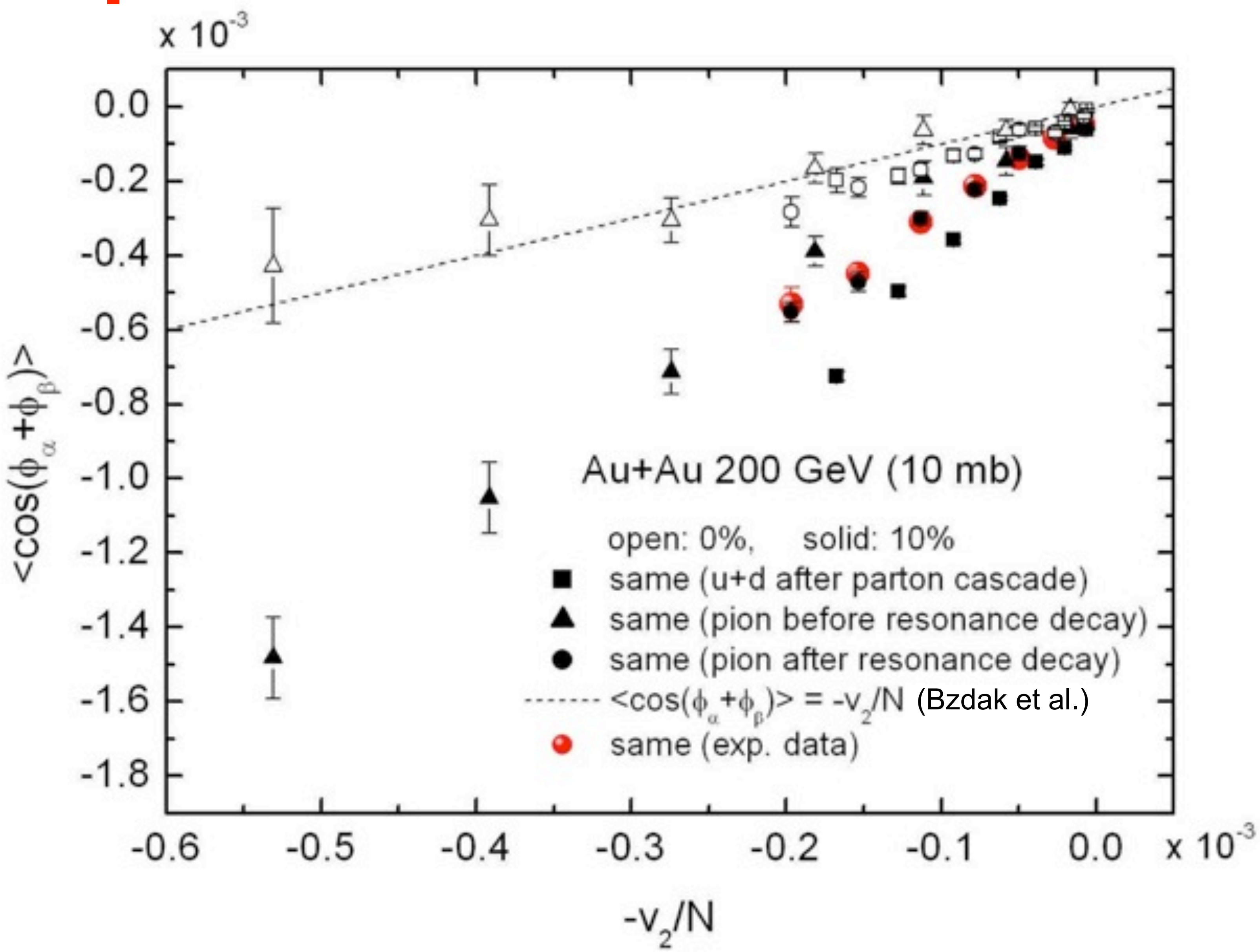




- Parton cascade reduces charge separation significantly.
- Coalescence recovers some charge separation in part because it reduces the number of particles after combining quarks into hadrons.
- Resonance decays reduce charge separation.

From a percentage of charge separation of 10% in the beginning, only 1-2% percentage remains at the end.

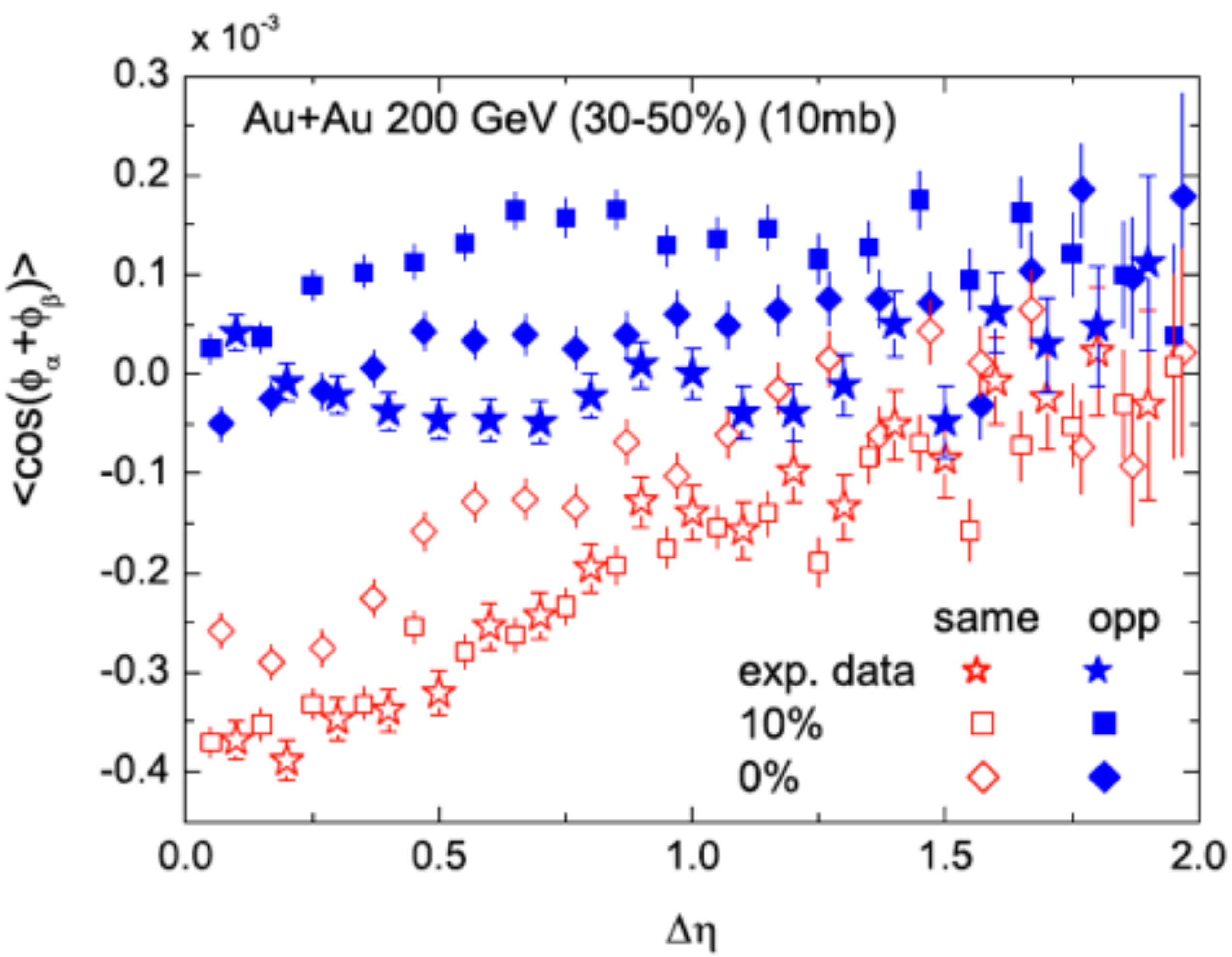
Charge separation vs trans. mom. conservation

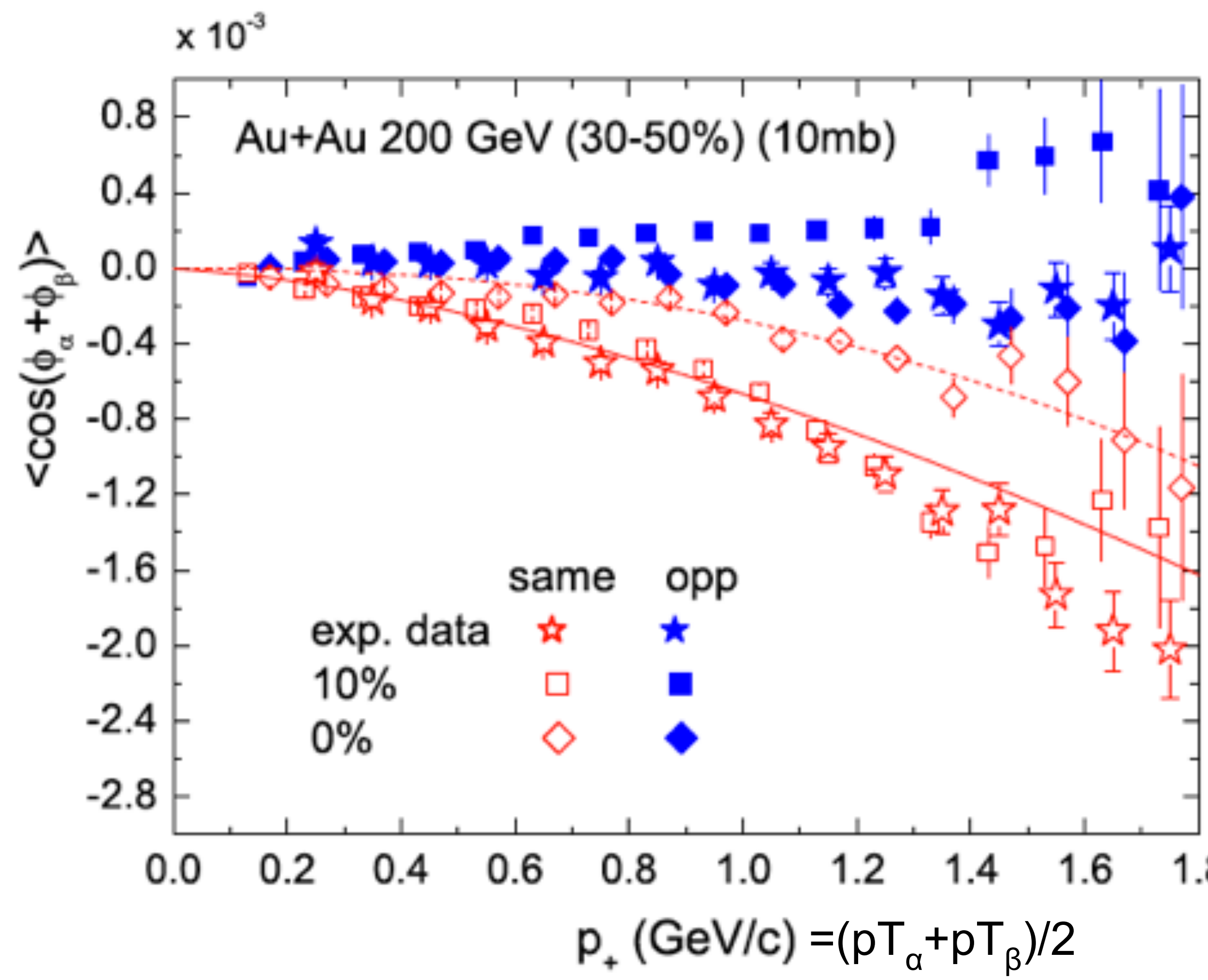


- AMPT results without initial charge separation are consistent with the expectation of transverse momentum conservation [dashed: $\langle\cos(\varphi_\alpha+\varphi_\beta)\rangle = -v_2/N$].

- Transverse momentum conservation can partly account for data, therefore initial charge separation or other mechanisms are needed.

Δη and p_T dependences of <cos($\varphi_\alpha+\varphi_\beta$)>





- AMPT results with initial charge separation can well describe same-charge data.
- AMPT results without initial charge separation are consistent with the expectation from transverse momentum conservation [dashed: <cos($\varphi_\alpha+\varphi_\beta$)> $\propto p_+^n$ (n=2~3)].

AMPT results about <cos(φ$_\alpha$-φ$_\beta$)>

$$\langle \cos[\phi_\alpha - \phi_\beta] \rangle = [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{in}] + [\langle a_\alpha a_\beta\rangle + B_{out}]$$

Non-flow/non-parity effects: can not cancel out

Directed flow: vanishes if measured in a symmetric rapidity range

P-even quantity: still sensitive to charge separation

- AMPT gives the same trends as data.
- Initial charge separation is not enough to make up for the large difference between AMPT and data.
- Other mechanisms?

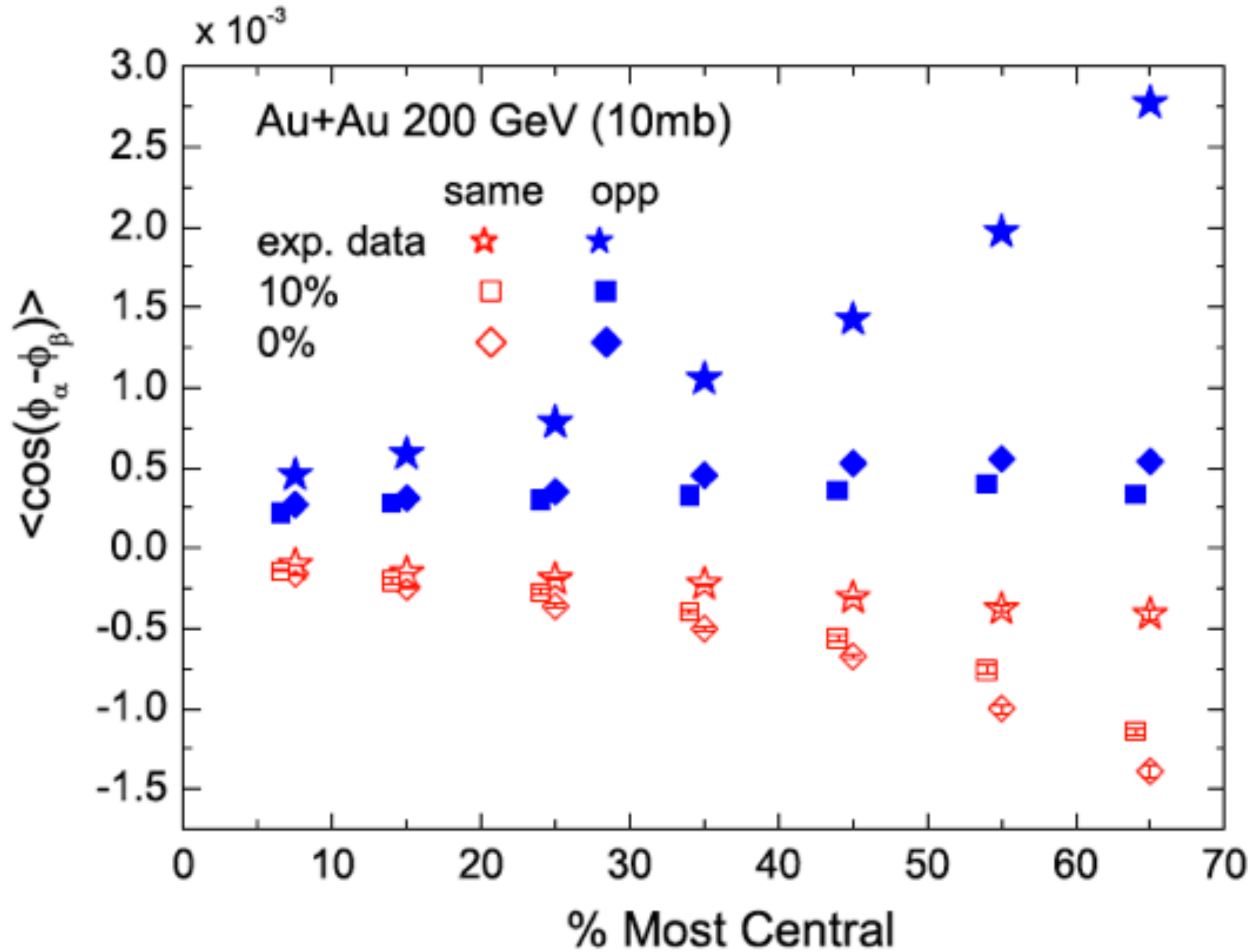
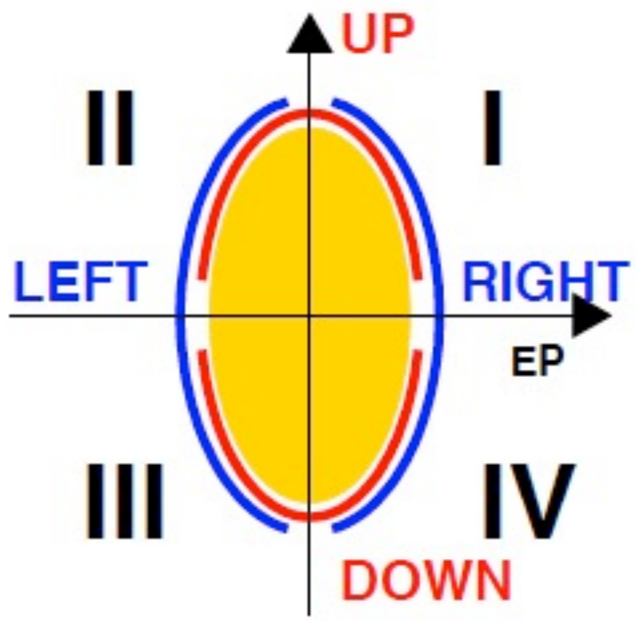


TABLE I. Estimated contributions to azimuthal correlations from various effects and comparison with data. The DATA are from the STAR measurement for AuAu 200-GeV collisions at ~50%–60% centrality.

Bzdak et. al., PRC **83**, 014905 (2011)

$\hat{O} \times 10^3$	$\langle\cos(\phi_1+\phi_2)\rangle_{++}$	$\langle\cos(\phi_1+\phi_2)\rangle_{+-}$	$\langle\cos(\phi_1-\phi_2)\rangle_{++}$	$\langle\cos(\phi_1-\phi_2)\rangle_{+-}$
CME	$-(0.1-1)$	$+(0.01-0.1)$	$+(0.1-1)$	$-(0.01-0.1)$
LCC	~ 0	$+(0.1-1)$	~ 0	$+(1-10)$
TMC	~ -0.1	~ -0.1	~ -1	~ -1
DATA	-0.45	$+0.06$	-0.38	$+1.97$

AMPT results about charge asymmetry correlations (I)



$$A_{+,UD} = (N_{+,U} - N_{+,D})/(N_{+,U} + N_{+,D}),$$

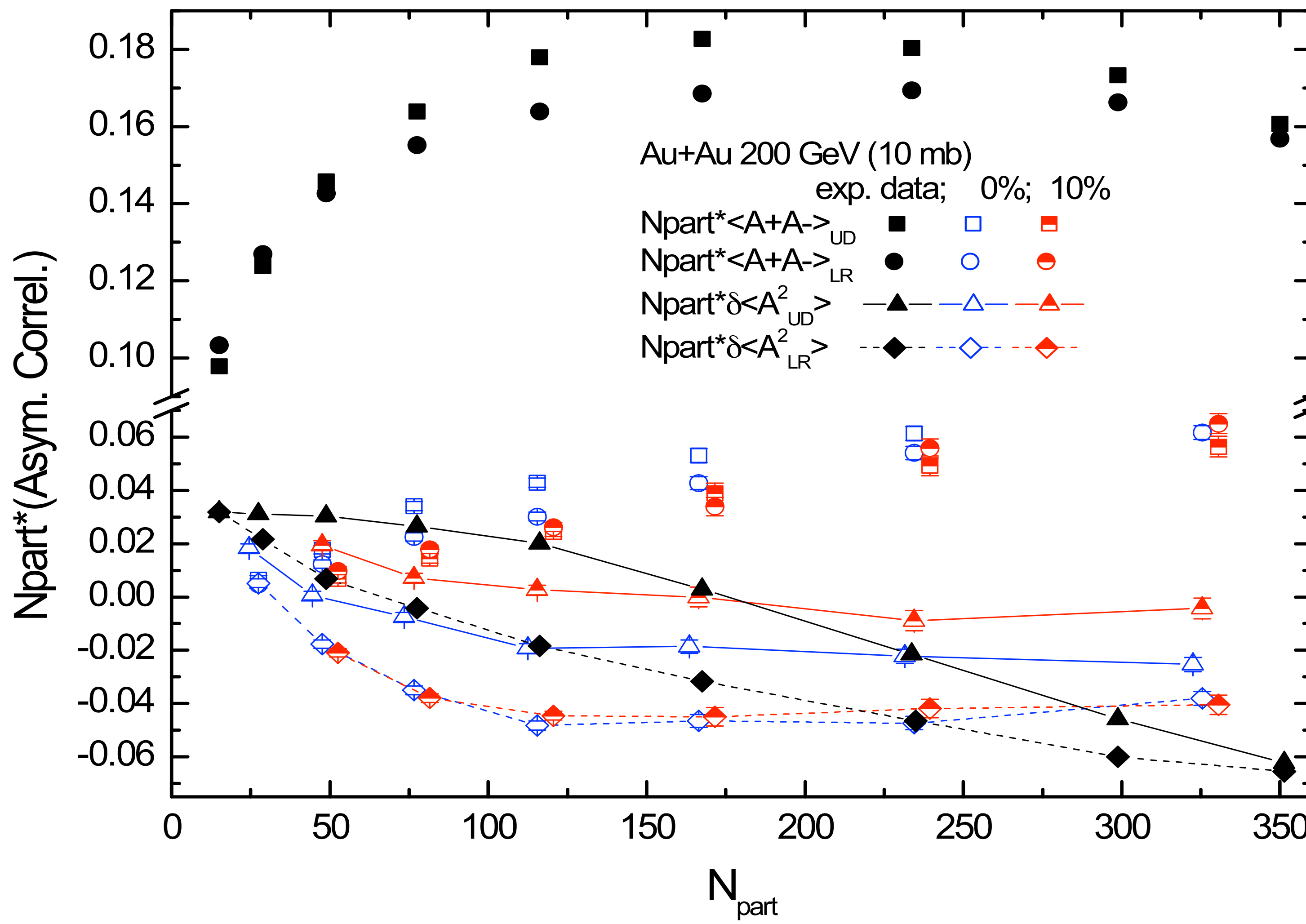
$$A_{-,UD} = (N_{-,U} - N_{-,D})/(N_{-,U} + N_{-,D}),$$

$$A_{+,LR} = (N_{+,L} - N_{+,R})/(N_{+,L} + N_{+,R}),$$

$$A_{-,LR} = (N_{-,L} - N_{-,R})/(N_{-,L} + N_{-,R}).$$

$$\delta\langle A^2_{\pm,UD}\rangle = \langle A^2_{\pm,UD}\rangle - \langle A^2_{\pm,UD,stat+det}\rangle,$$

$$\delta\langle A^2_{\pm,LR}\rangle = \langle A^2_{\pm,LR}\rangle - \langle A^2_{\pm,LR,stat+det}\rangle,$$

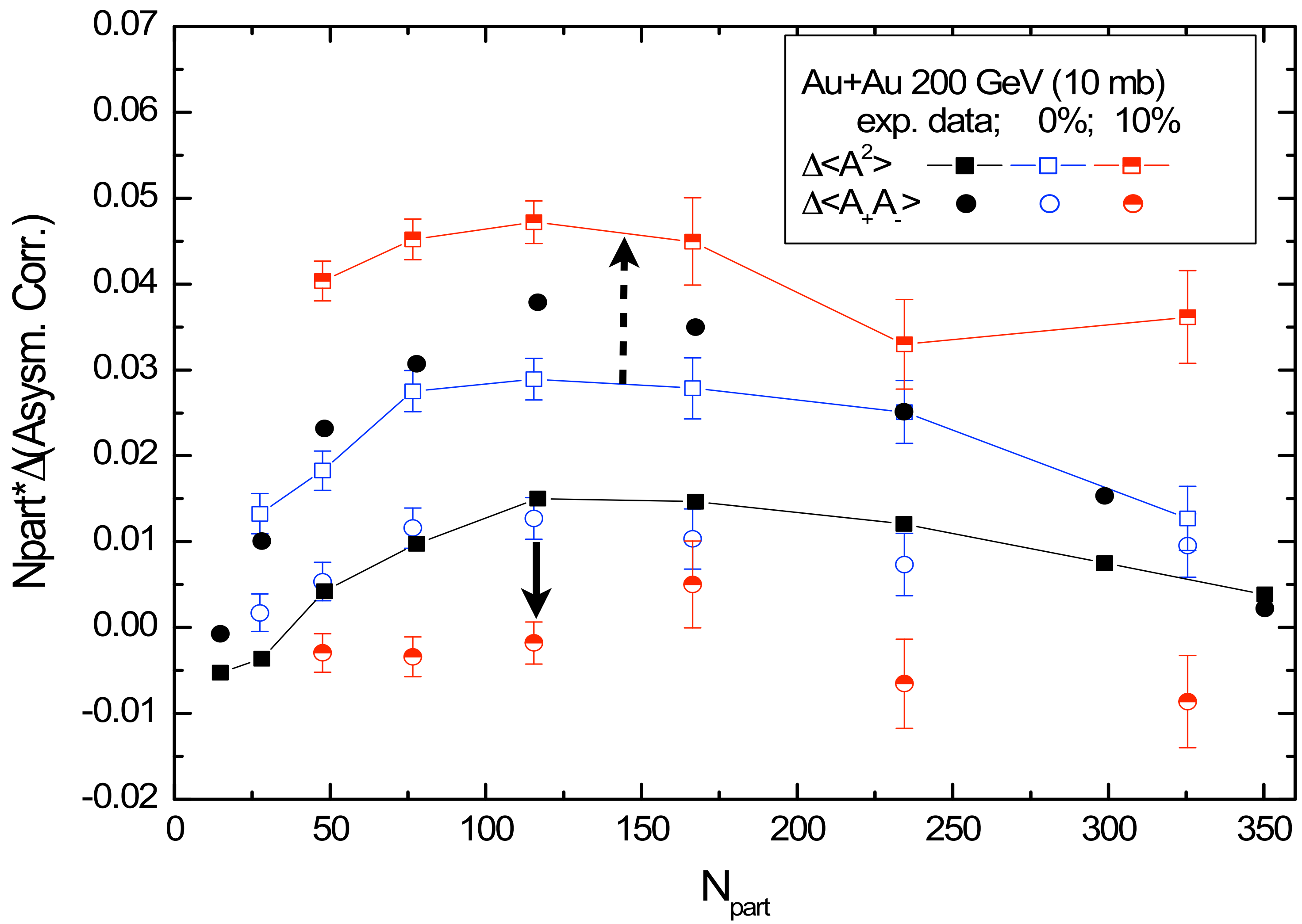


- For <A+A->, AMPT shows the similar trends as data, but smaller magnitudes.
- For <A²> , AMPT gives similar magnitudes for some centralities, but decreasing trends different from data.

AMPT results about charge asymmetry correlations (II)

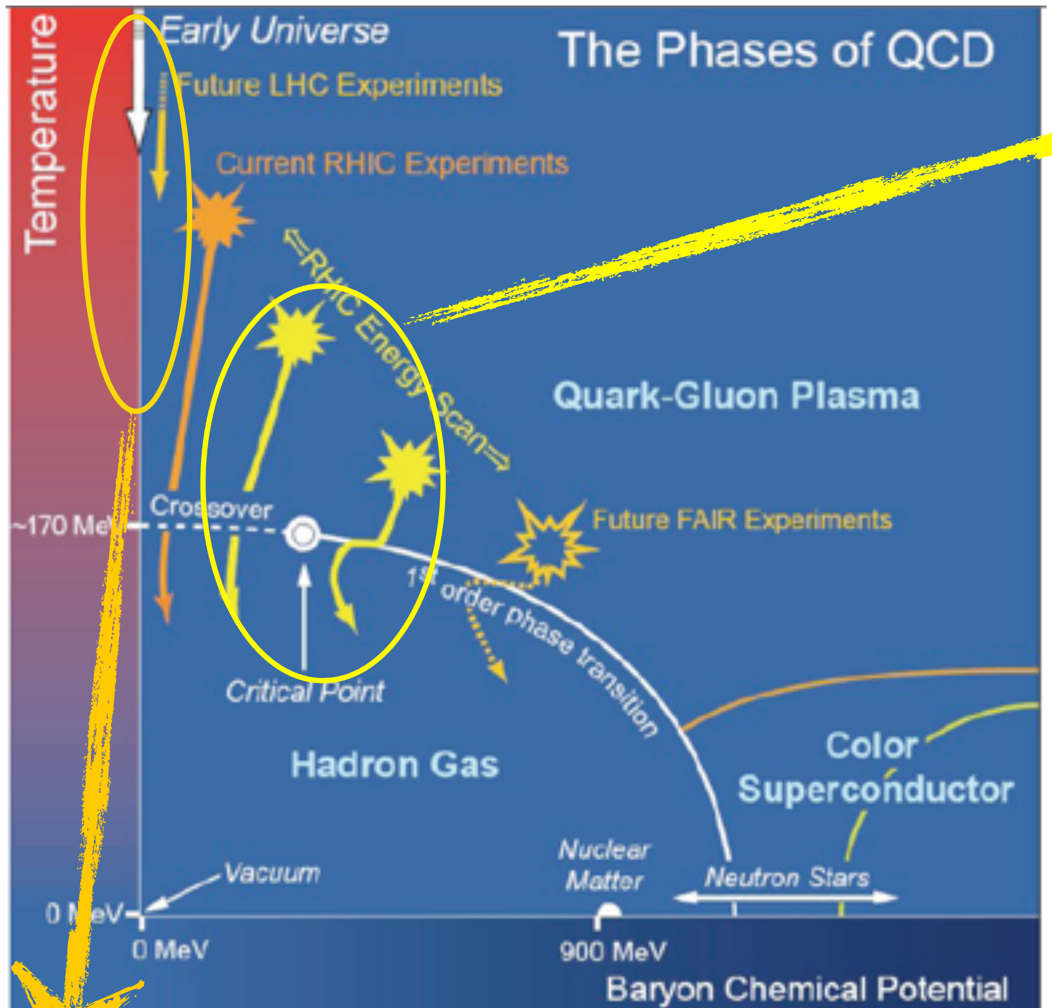
$$\Delta\langle A^2\rangle \equiv \delta\langle A^2_{\pm,UD}\rangle - \delta\langle A^2_{\pm,LR}\rangle \approx \langle A^2_{\pm,UD}\rangle - \langle A^2_{\pm,LR}\rangle,$$

$$\Delta\langle A_+A_-\rangle \equiv \langle A_+A_-\rangle_{UD} - \langle A_+A_-\rangle_{LR},$$



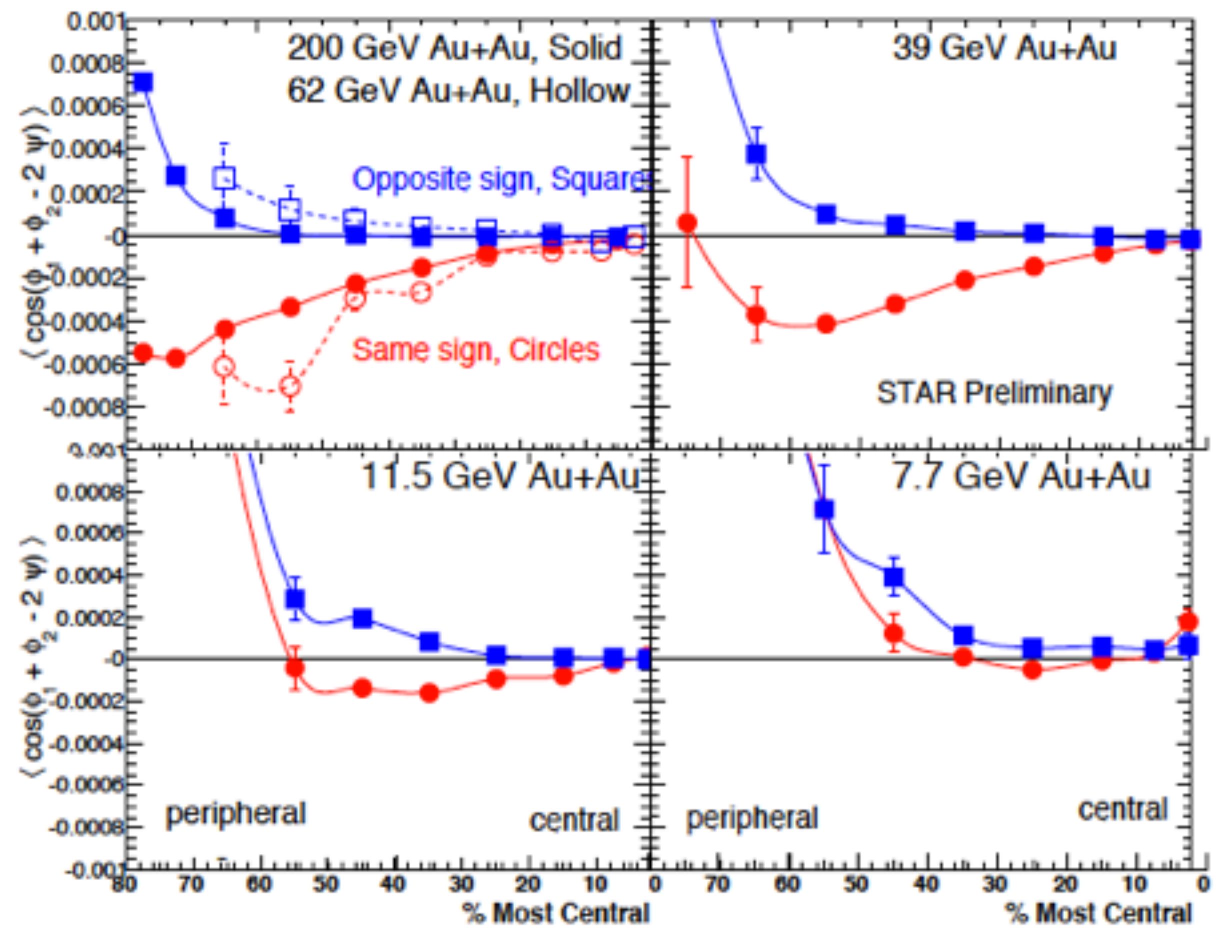
- For Δ<A+A-> and Δ<A²>, AMPT shows the similar trends as data, but can not match the data.
- Initial charge separations increase Δ<A²> and decrease Δ<A+A->, which is consistent with CME expectations.
- More detail studies are needed to understand the charge asymmetry data.

NEW DATA：two energy directions

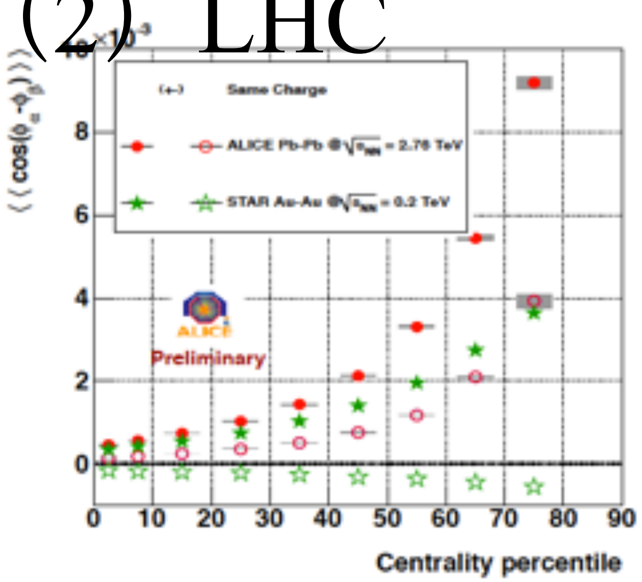


（1） RHIC

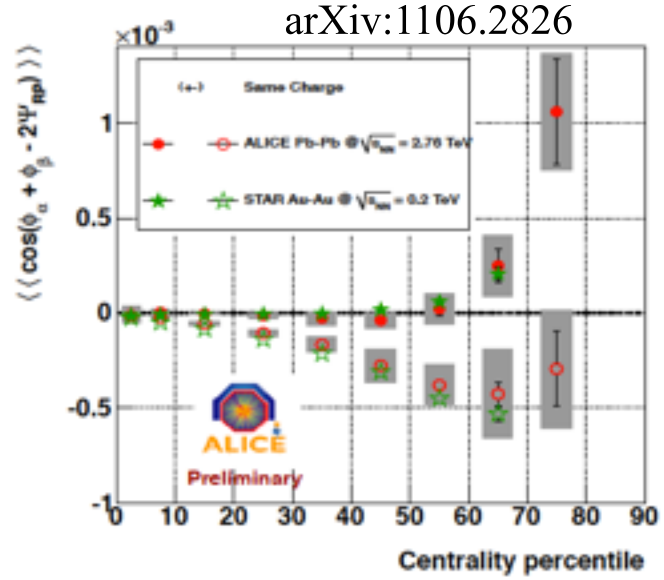
arXiv:1106.5902



（2） LHC

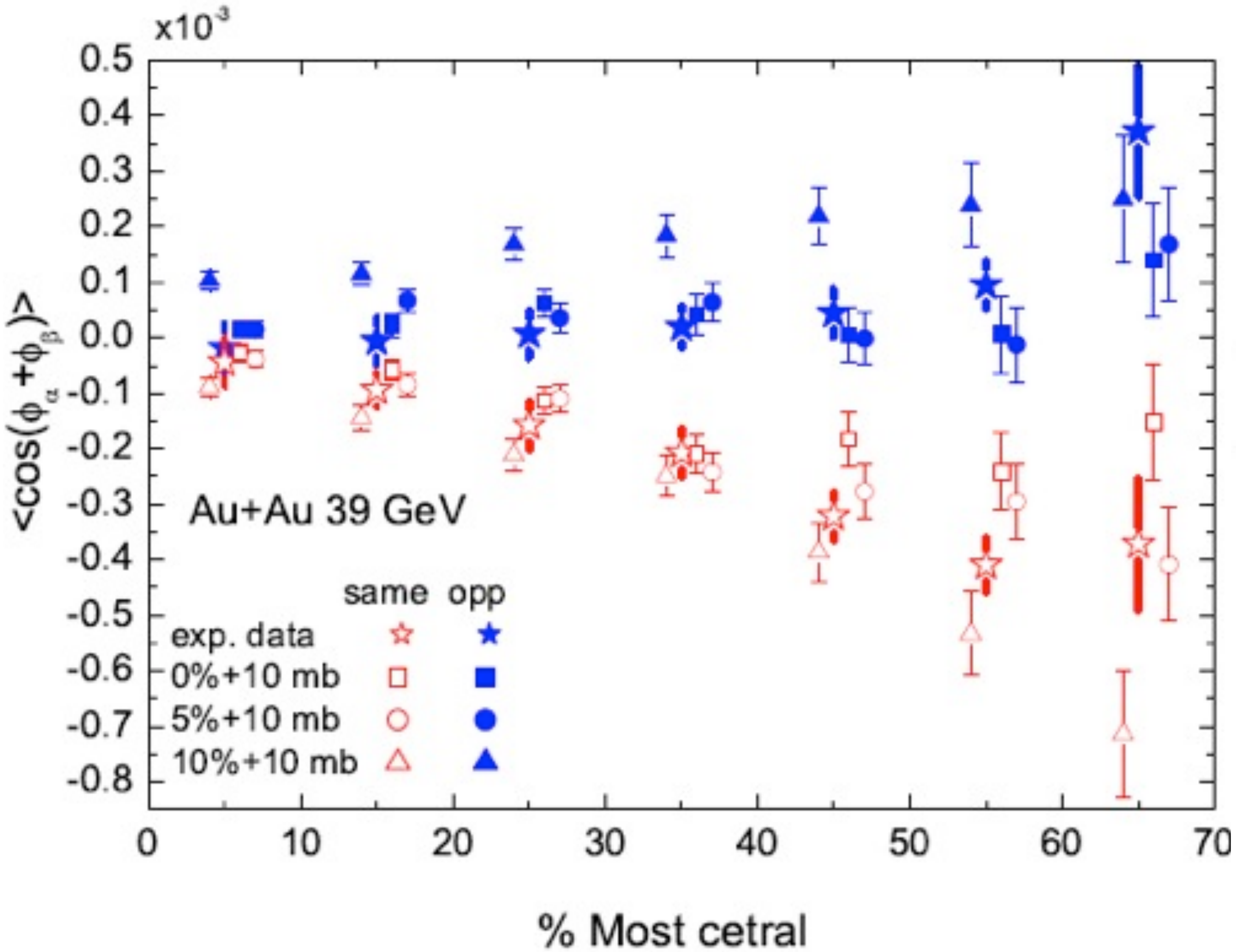


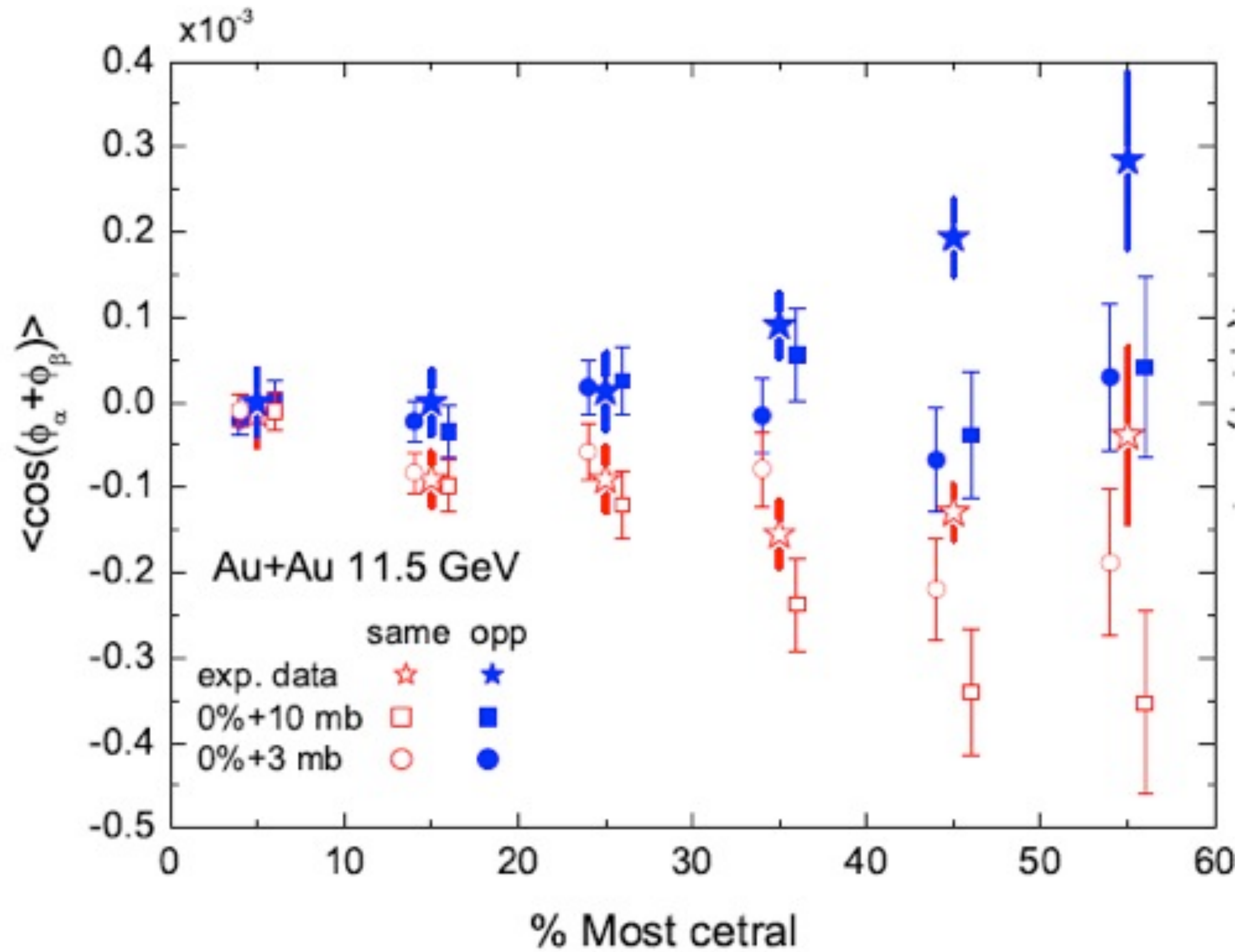
arXiv:1106.2826



- With decreasing of RHIC energy, same- and opposite-charge correlations become closer and positive.
- <cos($\varphi_\alpha+\varphi_\beta$)> at LHC is consistent with that at RHIC, but <cos($\varphi_\alpha-\varphi_\beta$)> at LHC is different from that at RHIC。
- The new exp. data require model explanations.

$\langle\cos(\varphi_\alpha+\varphi_\beta)\rangle$ at low RHIC energies

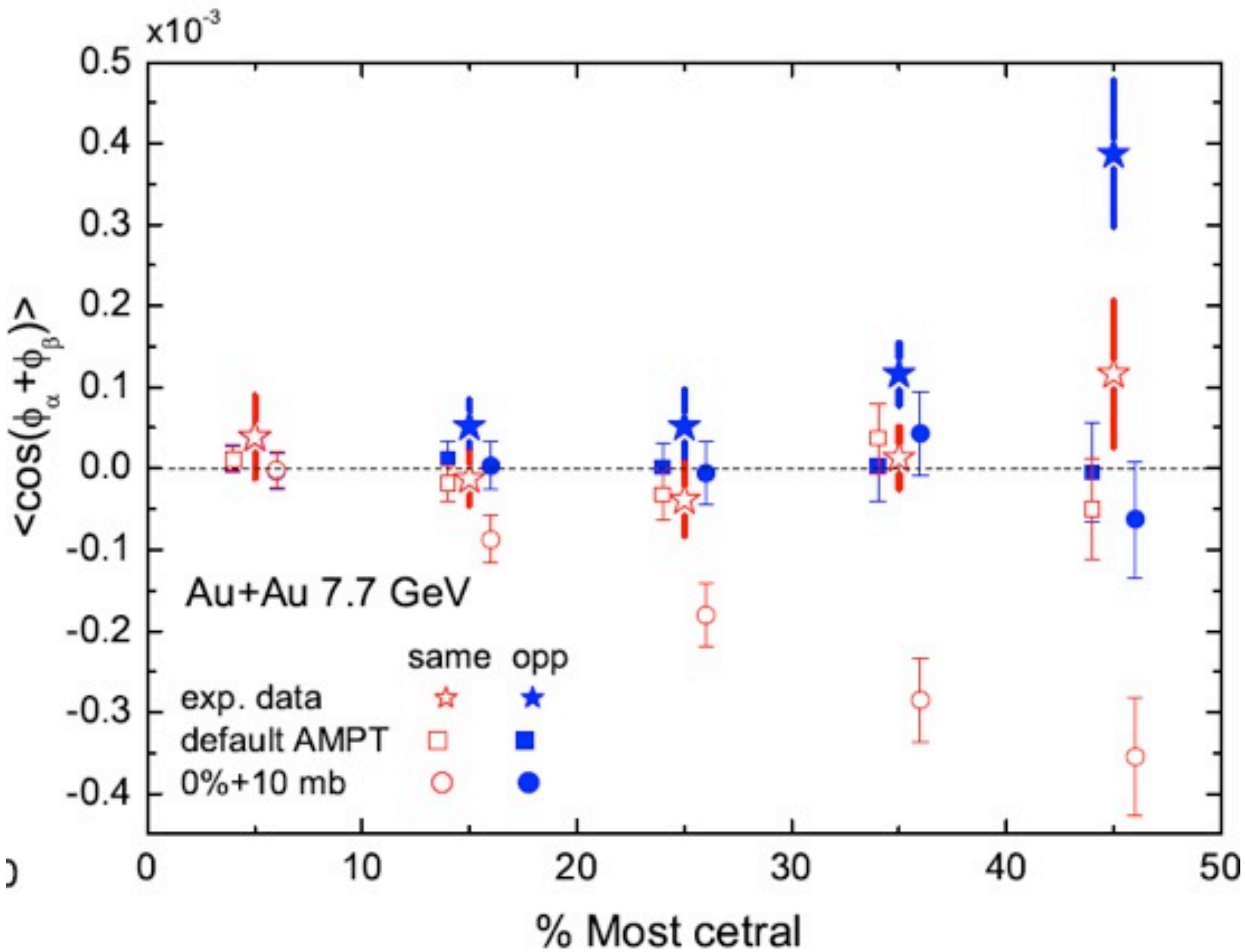




- The percentage of initial charge separation decreases from ~10% for 200 GeV , ~5% for 39 GeV (circles), to ~0% for 11.5 GeV(circles).

Initial charge separation effect decreases with the decreasing of energy.

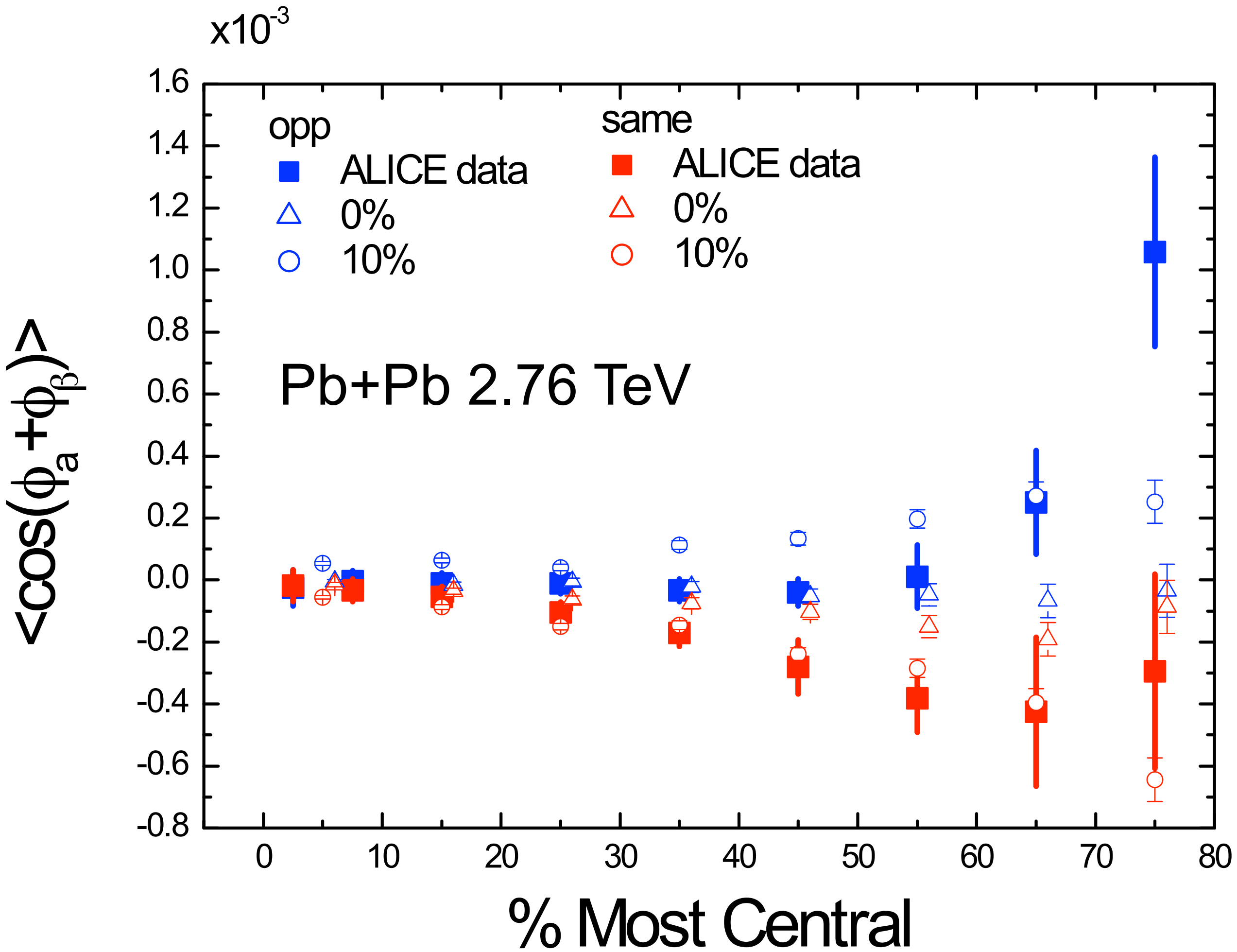
<cos(φα+φβ)> for Au+Au 7.7 GeV

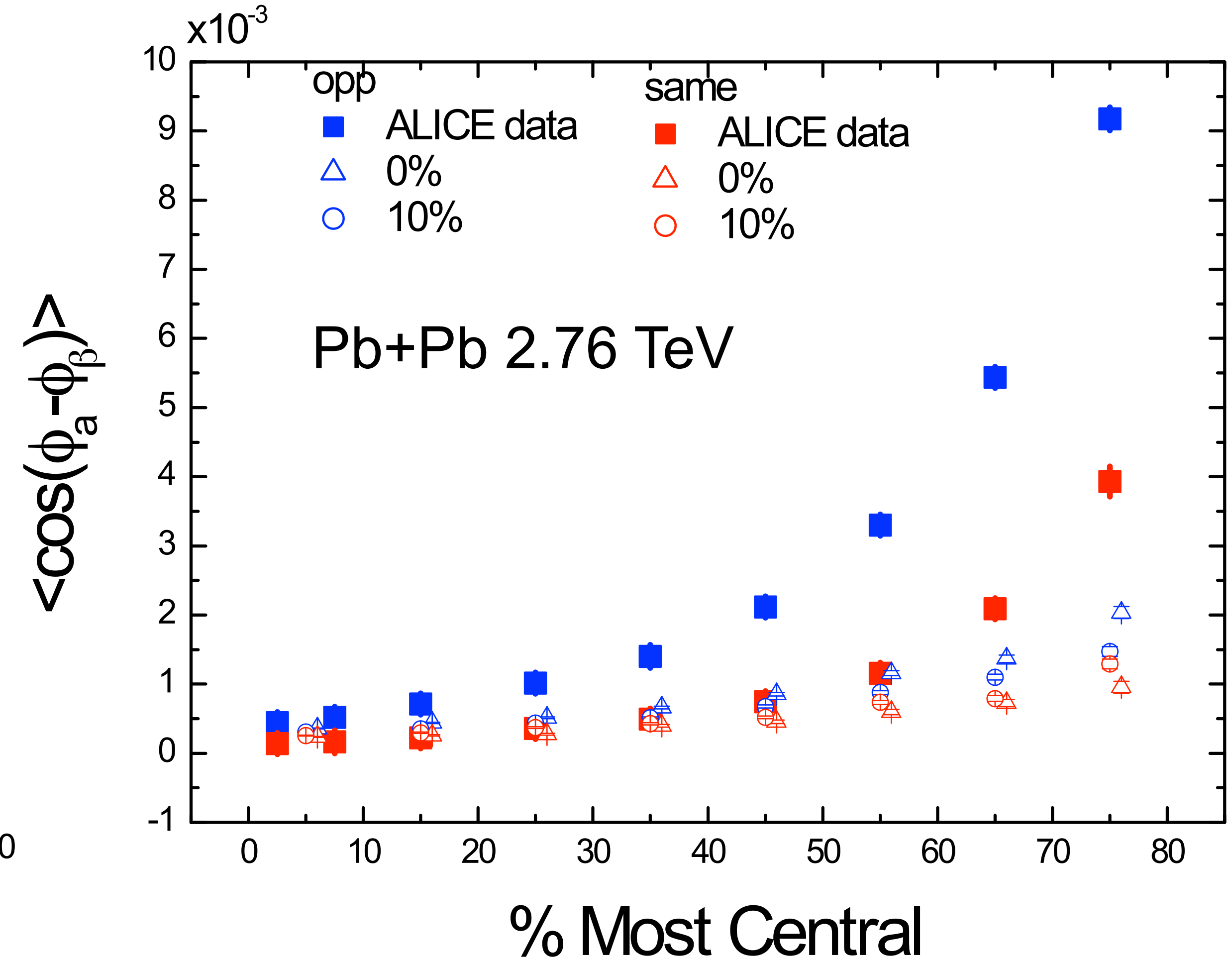


● The partonic interaction cross section decreases from ~10mb for 200 GeV, ~3mb for 11.5 GeV, to no partonic but hadronic interactions only for 7.7 GeV.

The partonic degree of freedom decreases with the decreasing of energy.

$<\cos(\varphi_\alpha \pm \varphi_\beta)>$ at LHC energy





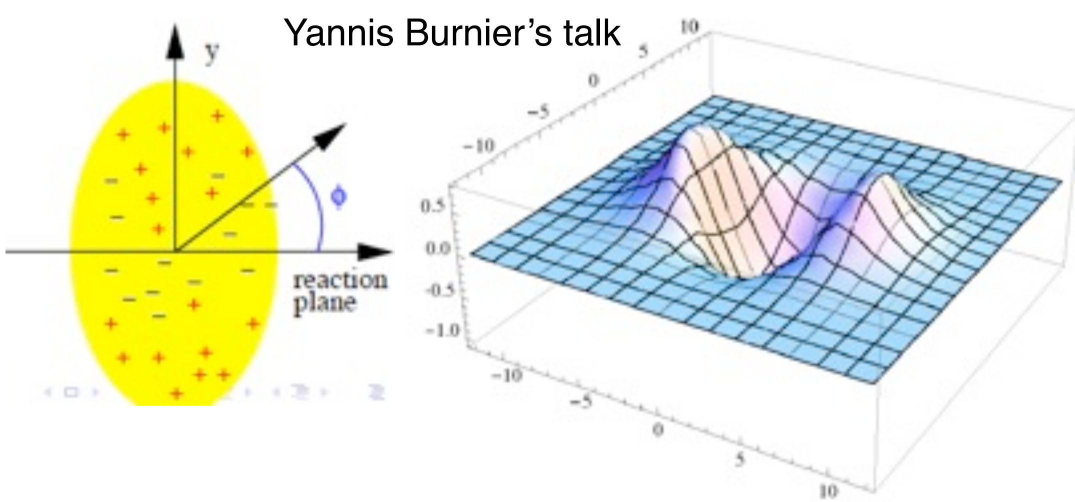
- For same-charge $<\cos(\varphi_\alpha+\varphi_\beta)>$, 10% initial charge separation can describe LHC data.
- For opposite-charge $<\cos(\varphi_\alpha+\varphi_\beta)>$, initial charge separation is not necessary for all centralities except 60-70% and 70-80%.
- For $<\cos(\varphi_\alpha-\varphi_\beta)>$, we only give the experimental trends, fail for the magnitudes.

Initial charge separation at LHC seems similar as that at top RHIC energy.

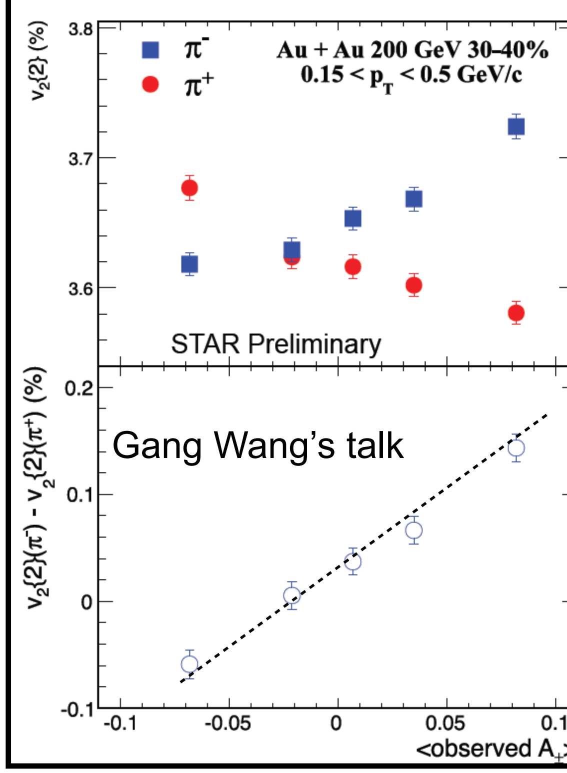
Outlook

- RBRC workshop (https://www.bnl.gov/pcp2012/)

Electric Quadrupole Moment
& chiral magnetic wave



Yannis Burnier, Dmitri Kharzeev, Jinfeng Liao, Ho-Ung Yee
PRL 107, 052303 (2011)



$$A_{\pm} = \frac{\overline{N}_{+} - \overline{N}_{-}}{\overline{N}_{+} + \overline{N}_{-}}$$

$$v_2^- - v_2^+ = 2\left(\frac{q_e}{\bar{\rho}_e}\right) A_{\pm}$$

- QM2012 (exp. & theory)

- ...

Summary

- final interactions play an important role, which can reduce the charge separation from 10% in the initial state to 1-2% in the final state.
- The initial charge separation mechanism or other mechanisms are needed in order to describe data for top RHIC energy and LHC energy.
- Charge azimuthal correlation is a helpful observable to learn phase transition for RHIC beam energy scan program.
- However, much more studies are required to understand all of the RHIC and LHC data.